Can TMT Image Habitable Planets ?

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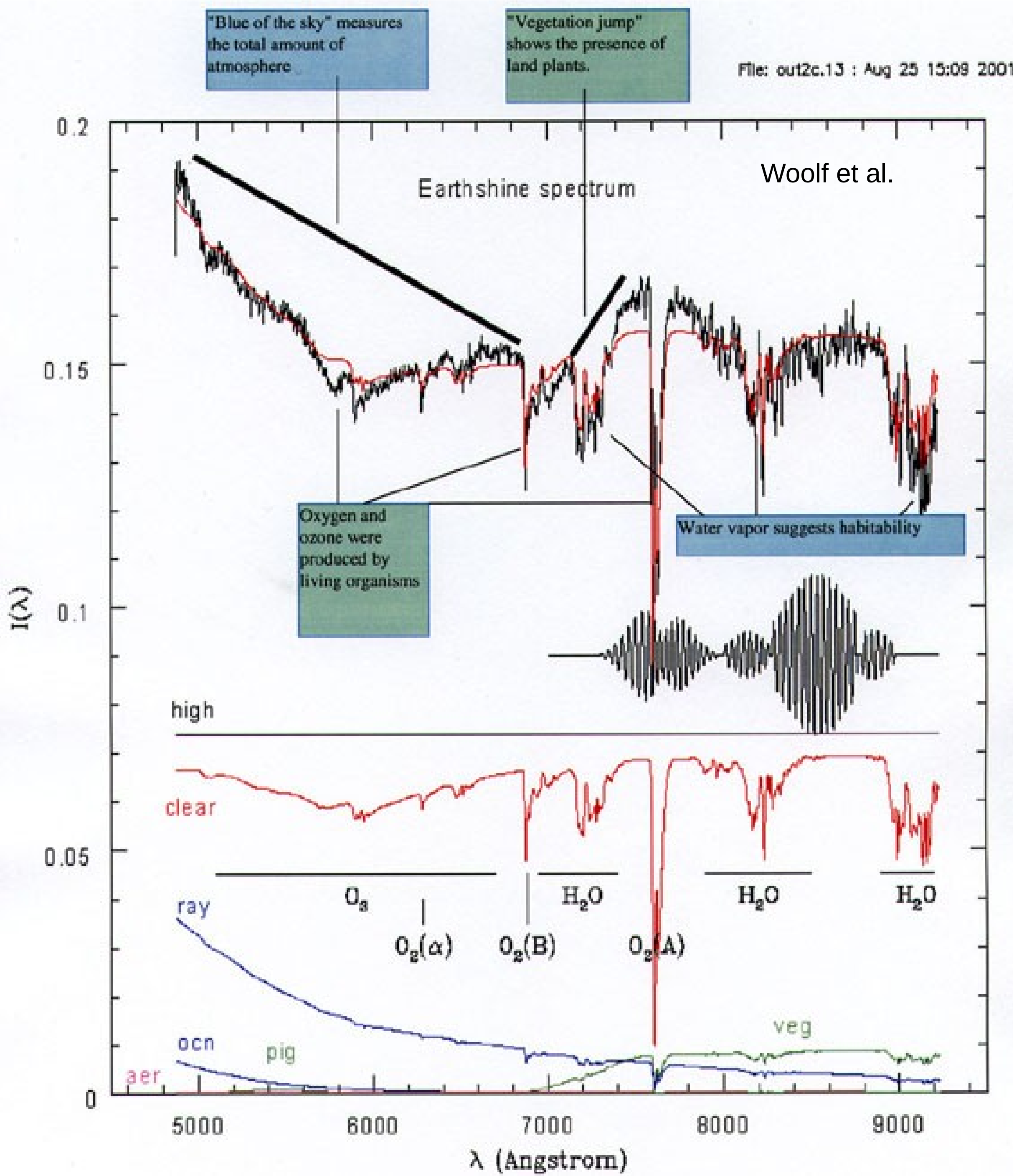
May 12, 2017

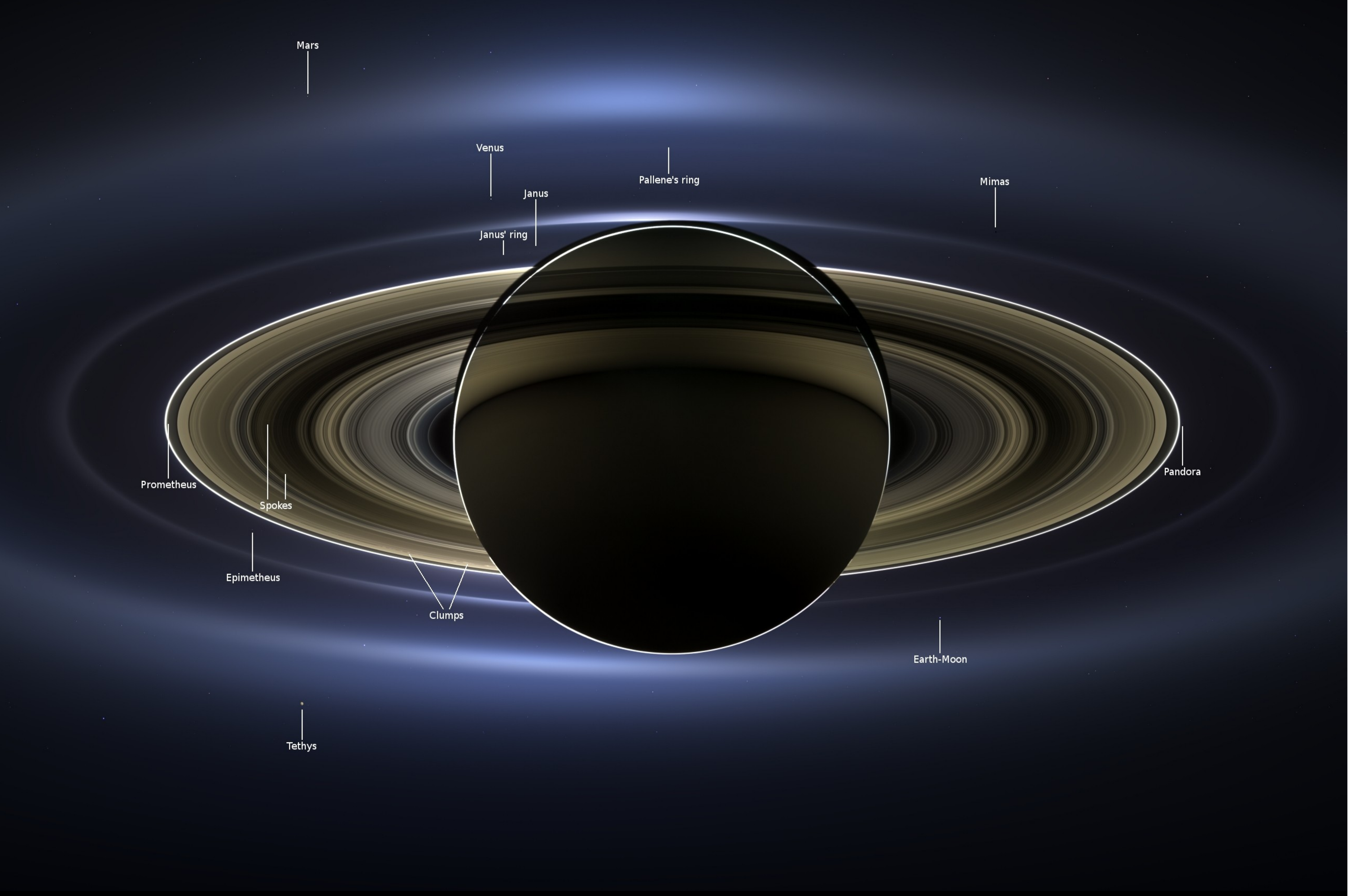
Why directly imaging ?

Spectra can also be obtained by transit, but :
- Low probability (few %)
- High atmosphere only

Spectra of Earth (taken by looking at Earthshine) shows evidence for life and plants

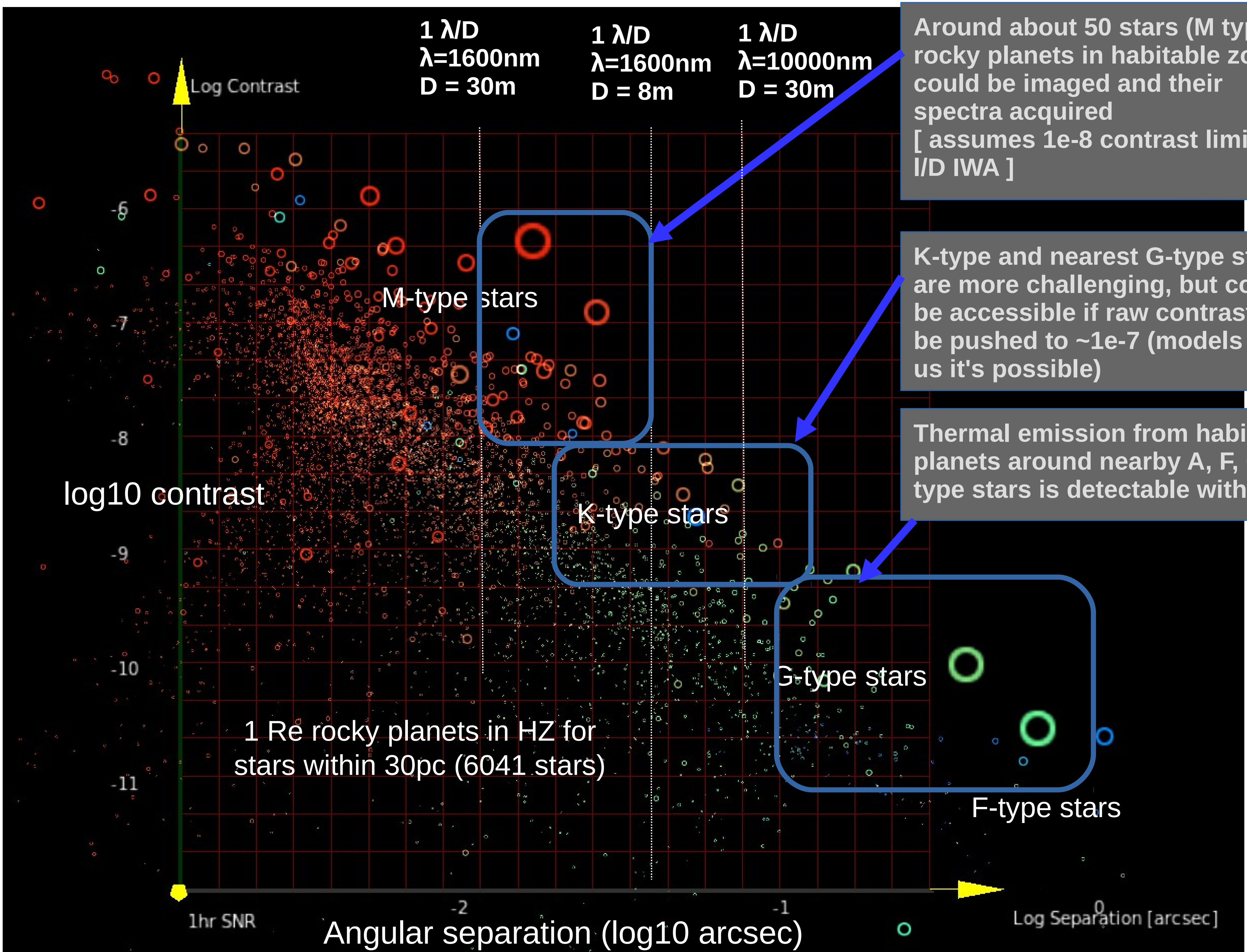


Taking images of exoplanets: Why is it hard ?




Saturn
Earth

Contrast and Angular separation

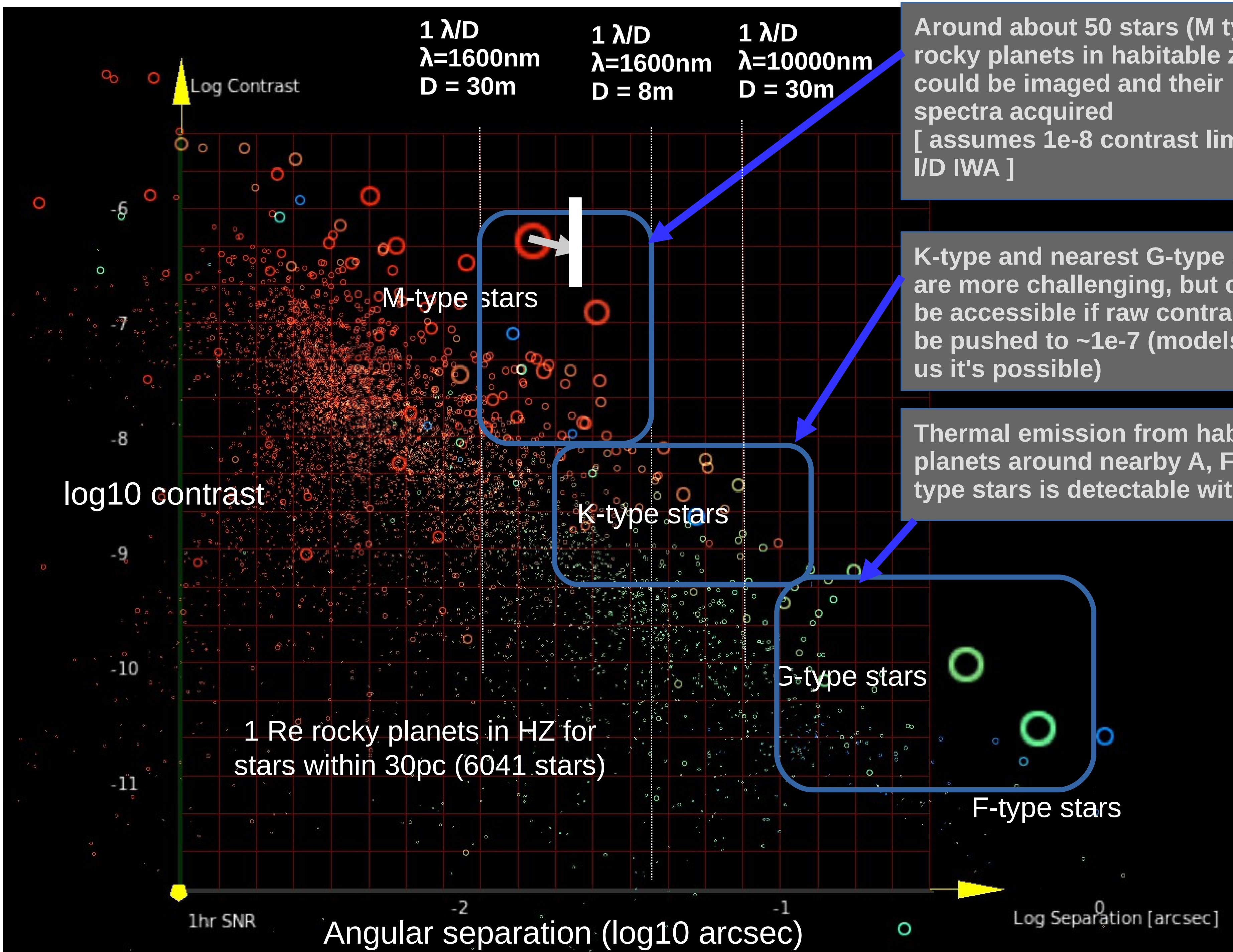


Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

Contrast and Angular separation (updated)



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Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

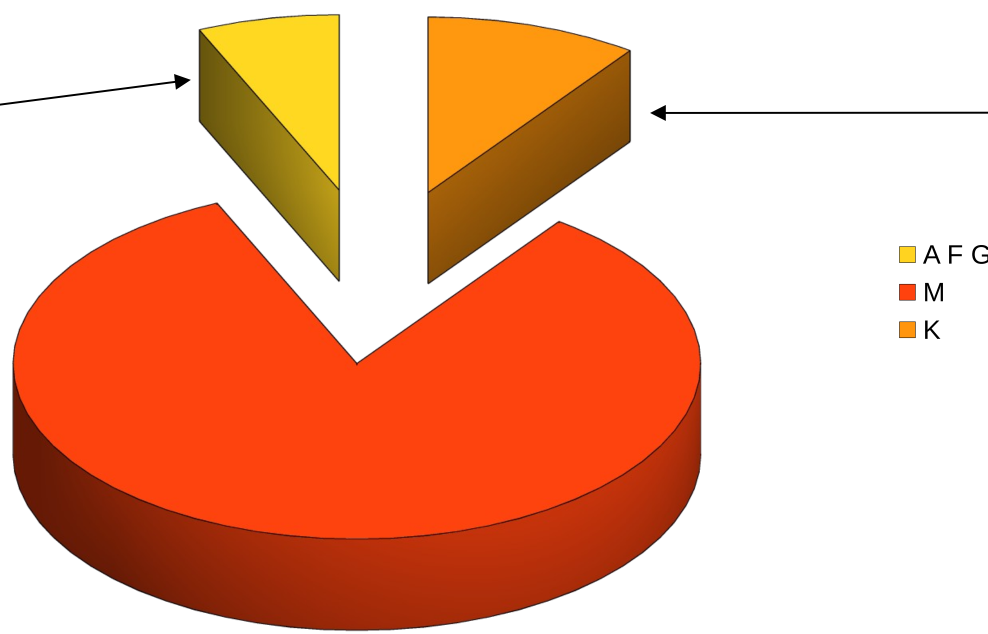
What is so special about M stars ?

They are **abundant**: >75% of main sequence stars are M type

Class	Effective temperature[1][2][3]	Vega-relative "color label"[4][nb 1]	Chromaticity[5][6][7][nb 2]	Main-sequence mass[1][8] (solar masses)	Main-sequence radius[1][8] (solar radii)	Main-sequence luminosity[1][8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[9]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	red	light orange red	0.08–0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Within 5pc (15ly) : 60 hydrogen-burning stars, 50 are M type, 6 are K-type, 4 are A, F or G

4.36 Alpha Cen A
8.58 Sirius A
11.40 Procyon A
11.89 Tau Ceti

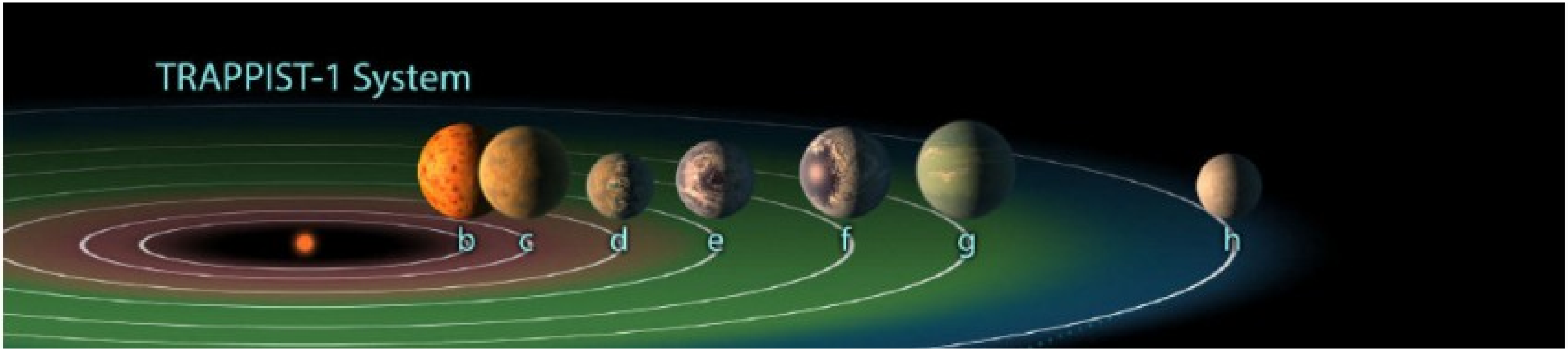


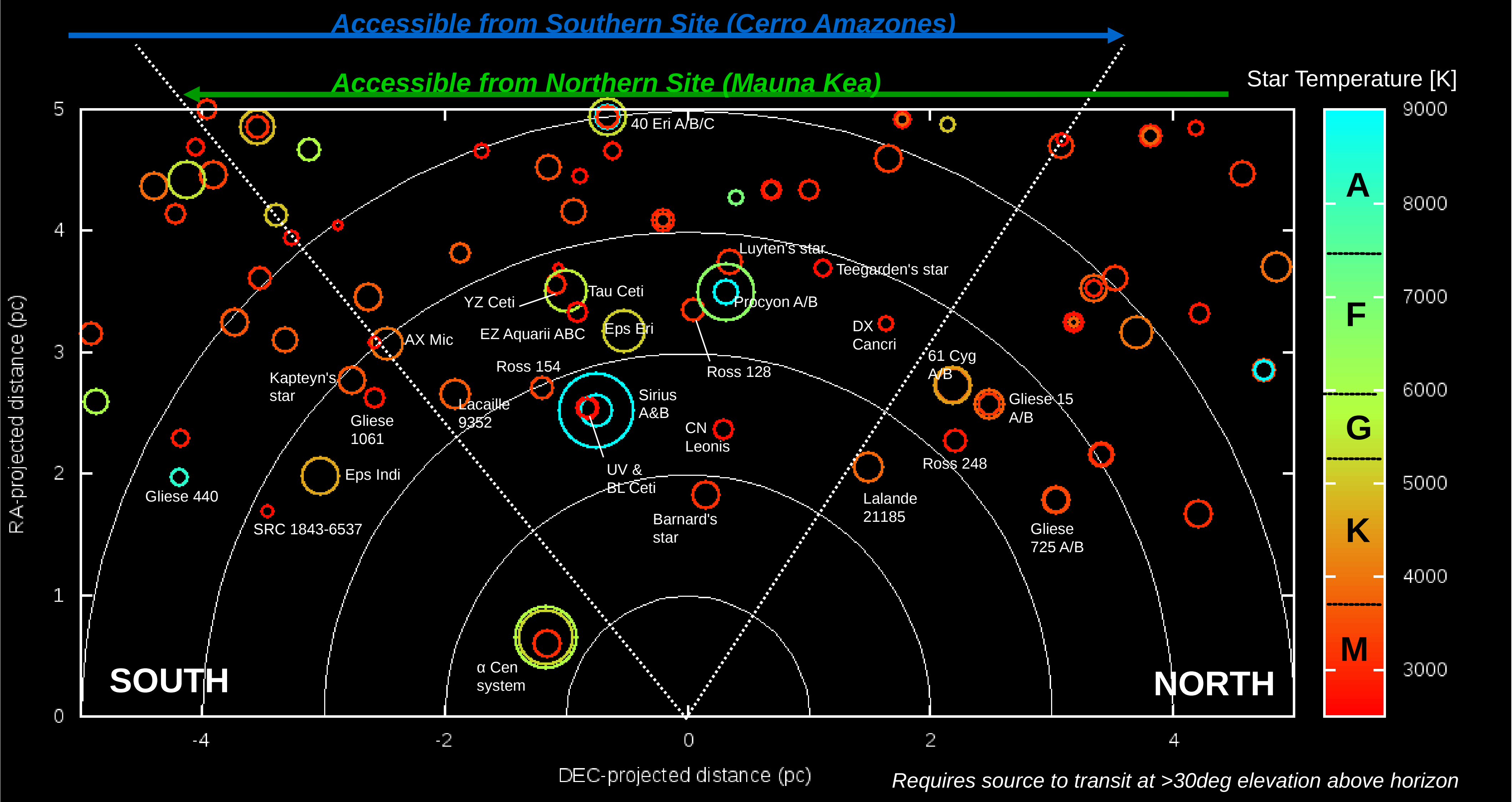
4.36 Alpha Cen B
10.52 Eps Eri
11.40 61 Cyg A
11.40 61 Cyg B
11.82 Eps Ind A
15.82 Gliese 380

What is so special about M stars ?

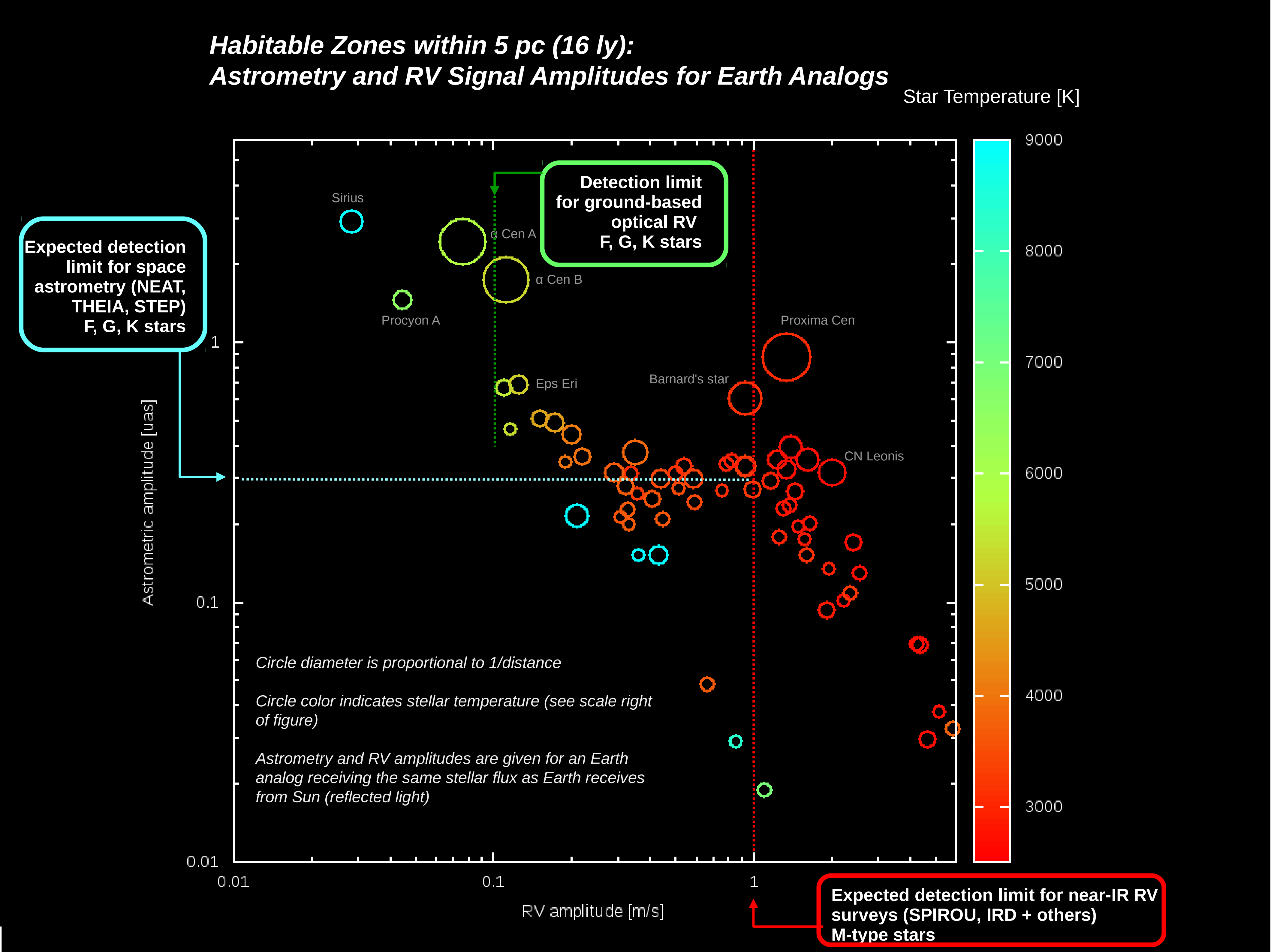
Strong evidence that their systems are **rich in terrestrial planets:**

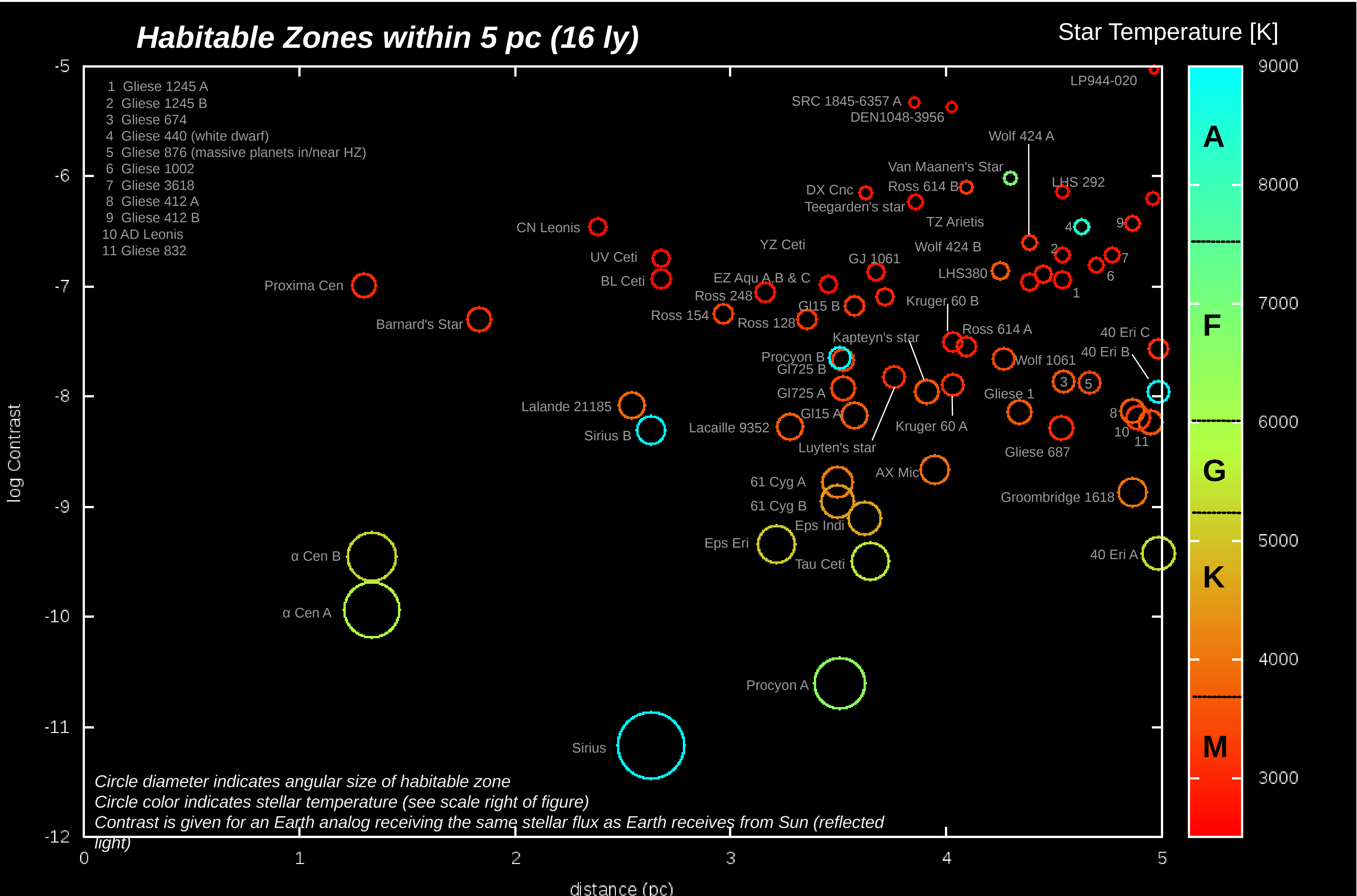
- Planet formation models evidence
- Lack of giant planets near HZ → good thing !
- Kepler data shows trend : more rocky planets around M-type stars
- Recent discoveries:
  Prox Cen b
  Trappist-1



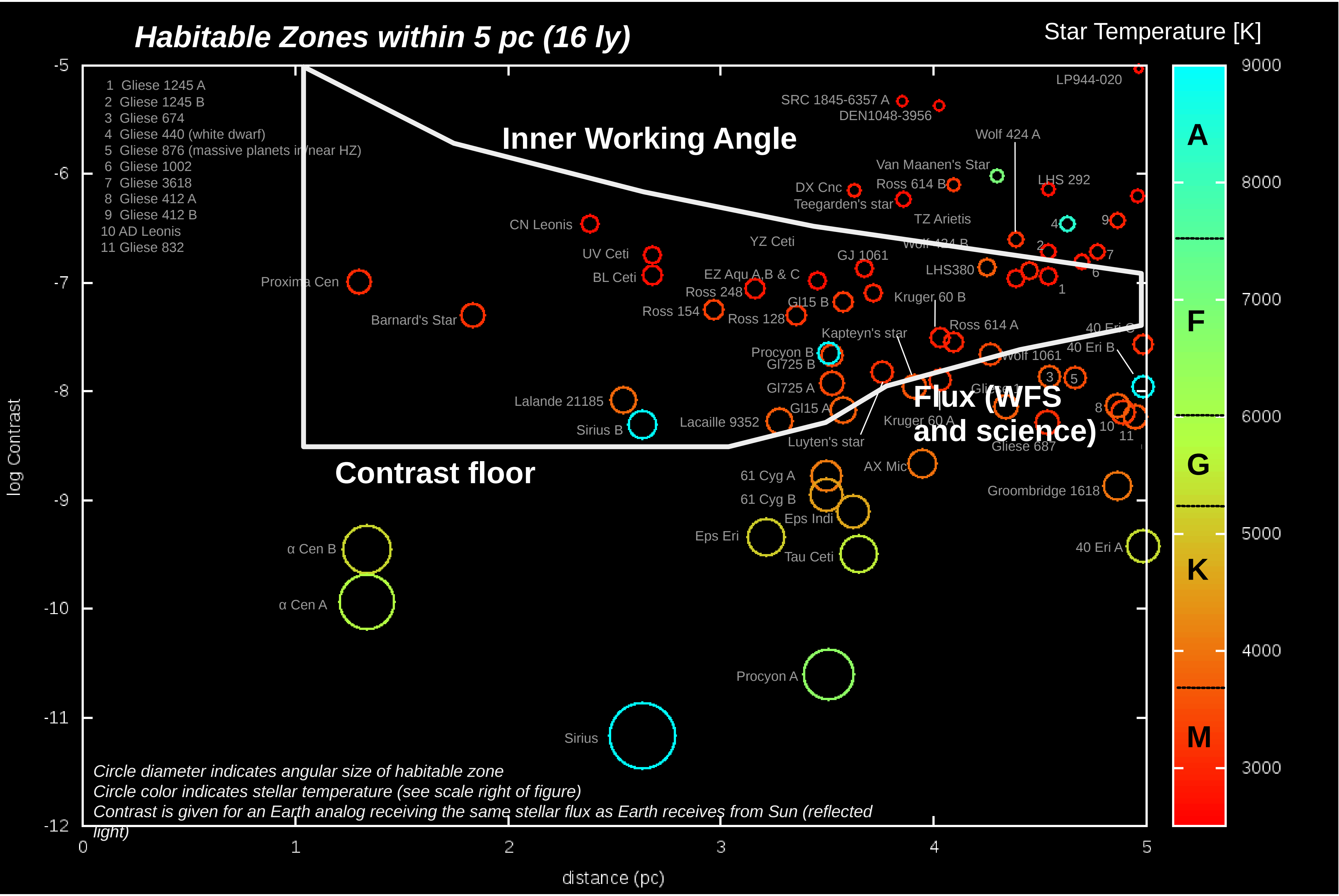


Accessible from Southern Site (Cerro Amazones)
Accessible from Northern Site (Mauna Kea)
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M
40 Eri A/B/C
Luyten's star
Teegarden's star
YZ Ceti
Tau Ceti
Procyon A/B
EZ Aquarii ABC
Eps Eri
DX Cancri
AX Mic
Ross 154
Ross 128
61 Cyg A/B
Kapteyn's star
Sirius A&B
Gliese 15 A/B
Gliese 1061
Lacaille 9352
CN Leonis
Ross 248
Eps Indi
UV & BL Ceti
Gliese 440
Lalande 21185
SRC 1843-6537
Barnard's star
Gliese 725 A/B
α Cen system
SOUTH
NORTH
RA-projected distance (pc)
DEC-projected distance (pc)
0
1
2
3
4
5
-4
-2
0
2
4
Requires source to transit at >30deg elevation above horizon


Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
Expected detection limit for space astrometry (NEAT, THEIA, STEP) F, G, K stars
Detection limit for ground-based optical RV F, G, K stars
Expected detection limit for near-IR RV surveys (SPIROU, IRD + others) M-type stars
Sirius
α Cen A
α Cen B
Procyon A
Proxima Cen
Barnard's star
Eps Eri
CN Leonis
Astrometric amplitude [uas]
1
0.1
0.01
RV amplitude [m/s]
0.01
0.1
1
Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)
Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)



Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
LP944-020
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Van Maanen's Star
DX Cnc
Ross 614 B
LHS 292
Teegarden's star
TZ Arietis
CN Leonis
YZ Ceti
Wolf 424 B
UV Ceti
GJ 1061
EZ Aqu A,B & C
LHS380
BL Ceti
Proxima Cen
Ross 248
Gl15 B
Kruger 60 B
Ross 154
Ross 128
Barnard's Star
Ross 614 A
40 Eri C
Kapteyn's star
40 Eri B
Procyon B
Gl725 B
Wolf 1061
Gl725 A
Gliese 1
Lalande 21185
Gl15 A
Lacaille 9352
Kruger 60 A
Sirius B
Luyten's star
Gliese 687
AX Mic
61 Cyg A
Groombridge 1618
61 Cyg B
Eps Indi
Eps Eri
α Cen B
Tau Ceti
40 Eri A
α Cen A
Procyon A
Sirius
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
log Contrast
-5
-6
-7
-8
-9
-10
-11
-12
distance (pc)
0
1
2
3
4
5
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M



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6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Inner Working Angle
Contrast floor
Flux (WFS and science)
LP944-020
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Van Maanen's Star
LHS 292
DX Cnc
Ross 614 B
Teegarden's star
TZ Arietis
CN Leonis
YZ Ceti
UV Ceti
GJ 1061
LHS380
BL Ceti
EZ Aqu A,B & C
Proxima Cen
Ross 248
Kruger 60 B
Gl15 B
Ross 154
Ross 128
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Circle diameter indicates angular size of habitable zone
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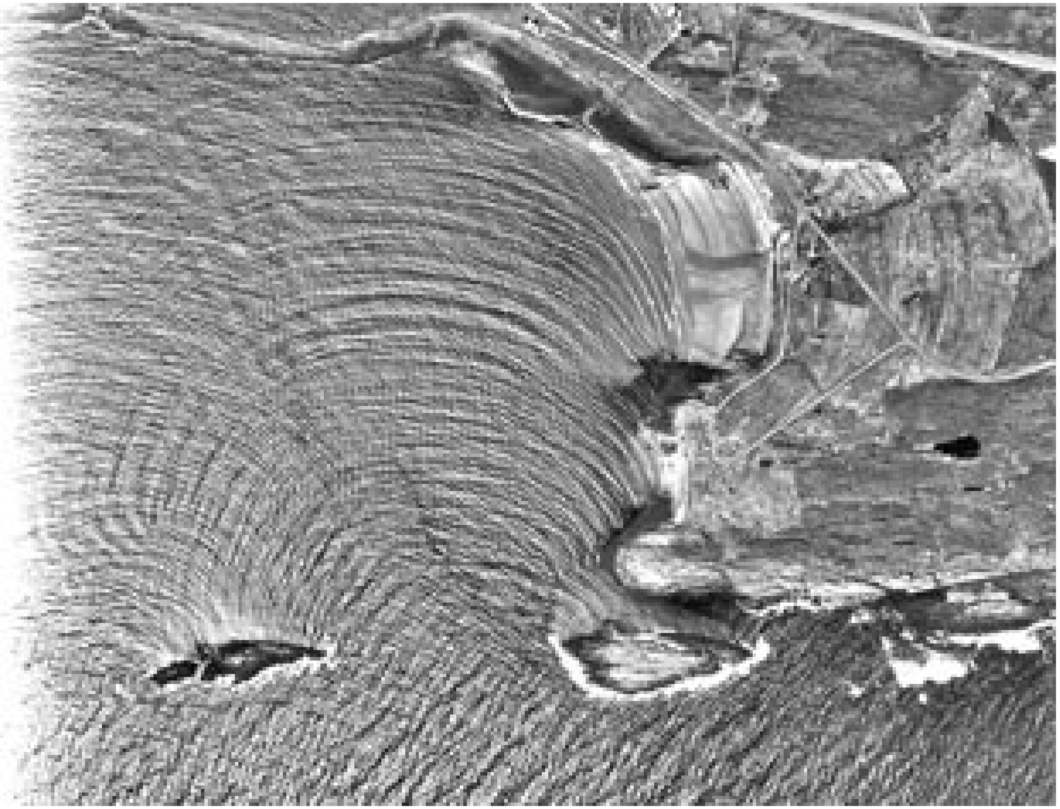
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
log Contrast
distance (pc)
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000

Coronagraphy … Using optics tricks to remove starlight (without removing planet light)

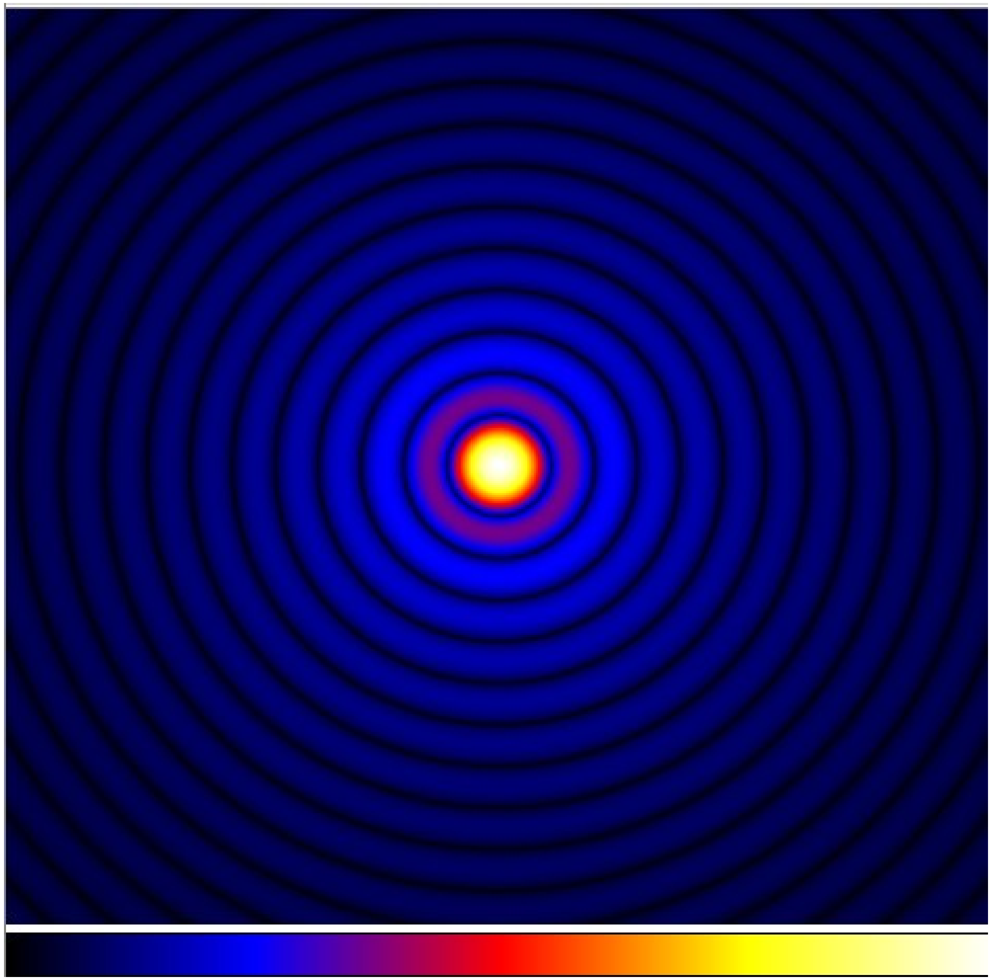
← Olivier's thumb...
the easiest coronagraph
Doesn't work well enough to
see planets around other stars

We need a better coronagraph... and a larger eye (telescope)

Water waves diffract around obstacles, edges, and so does light

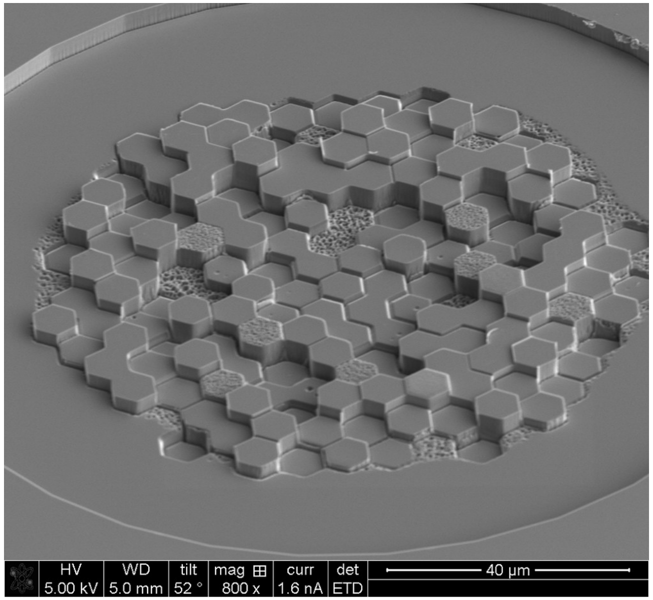


Waves diffracted by coastline and islands

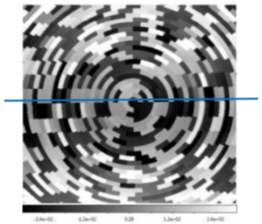


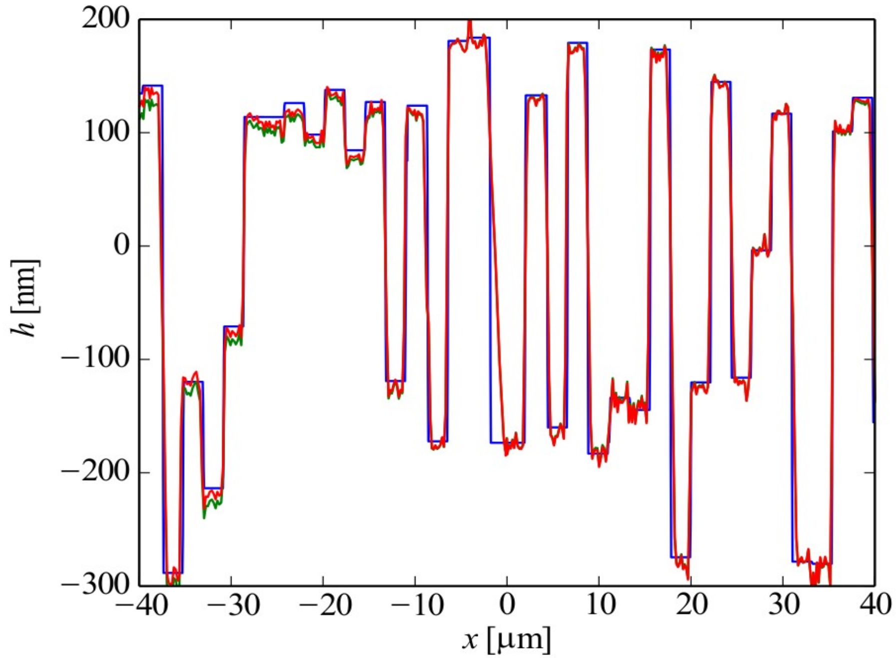
Ideal image of a distant star by a telescope
Diffraction rings around the image core

PIAACMC focal plane mask manufacturing

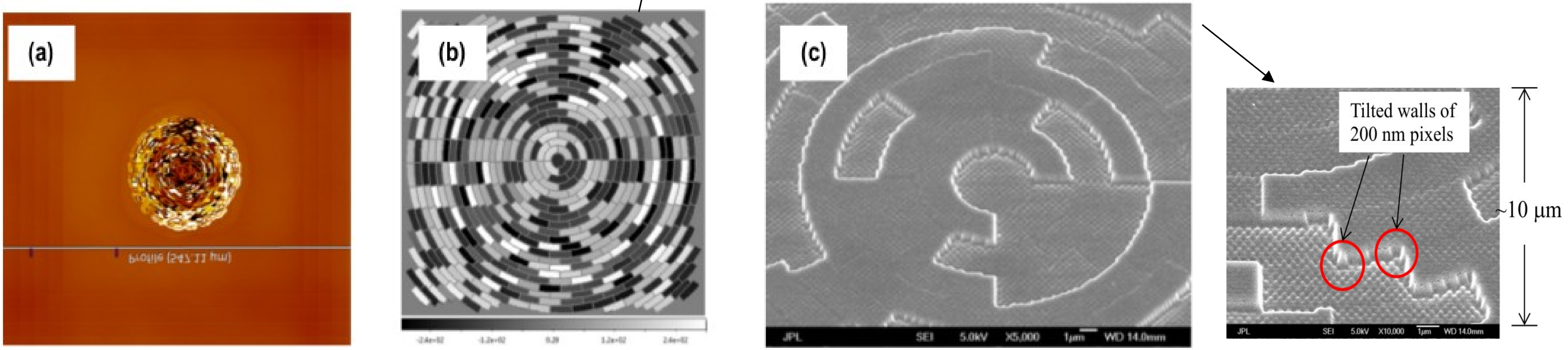


← SCExAO focal plane mask (Mar 2017)





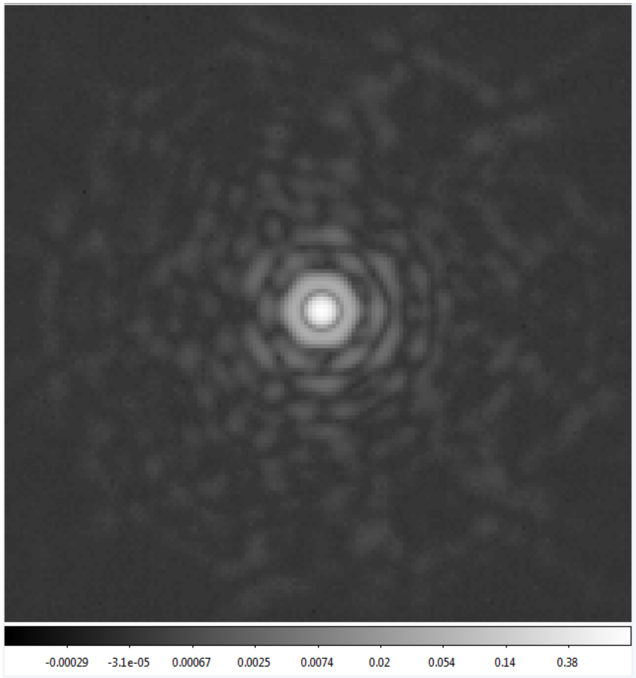
Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)



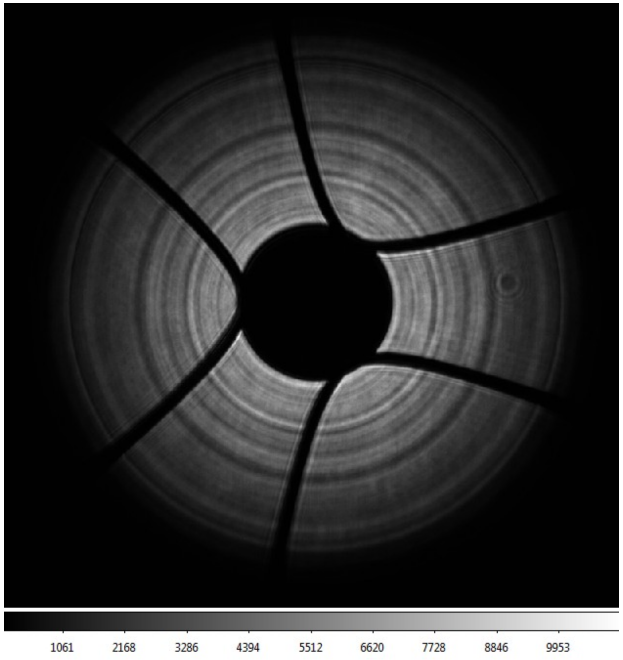
PIAACMC lab performance @ WFIRST (Kern et al. 2016)

Operates at 1e-7 contrast, 1.3 l/D IWA, 70% throughput
Visible light

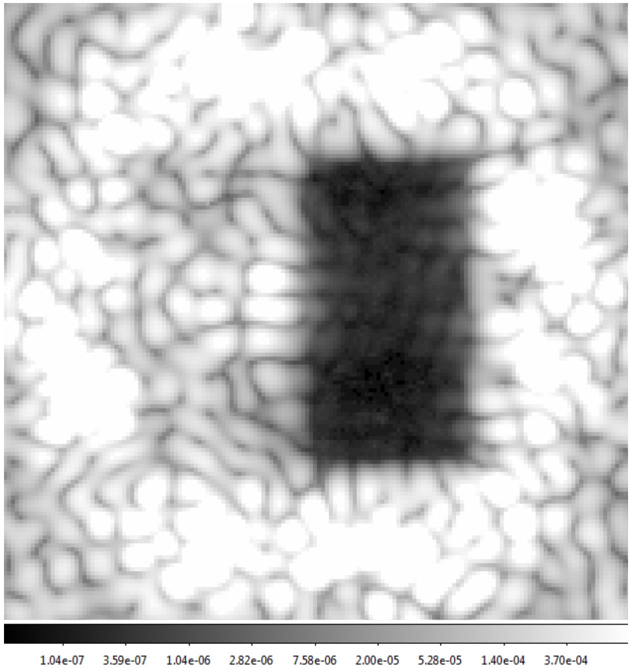
non-coronagraphic PSF



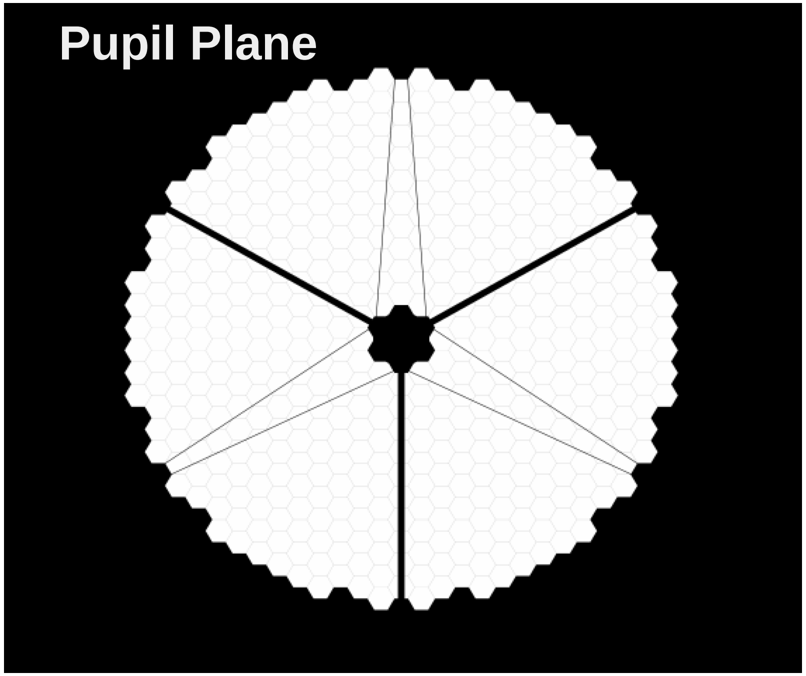
Remapped pupil

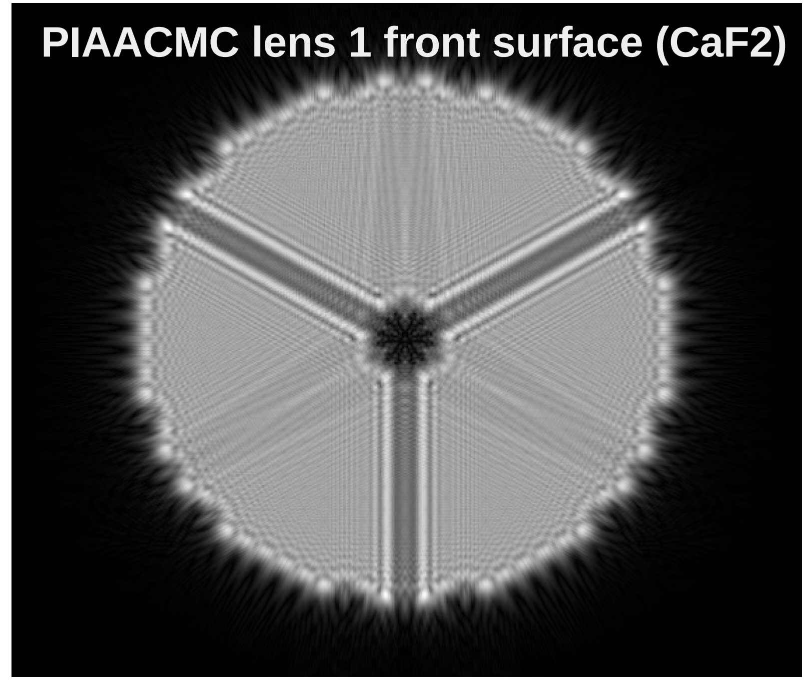


Coronagraphic image

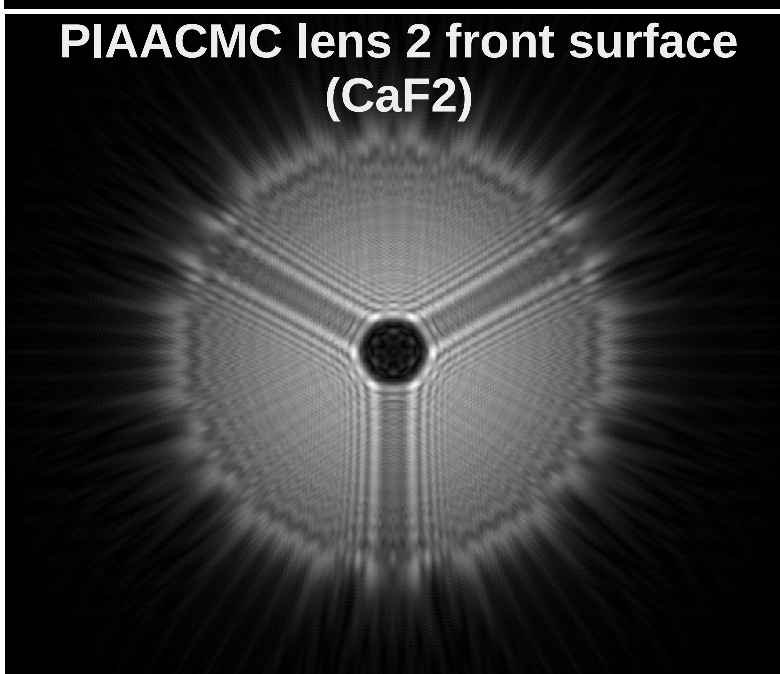


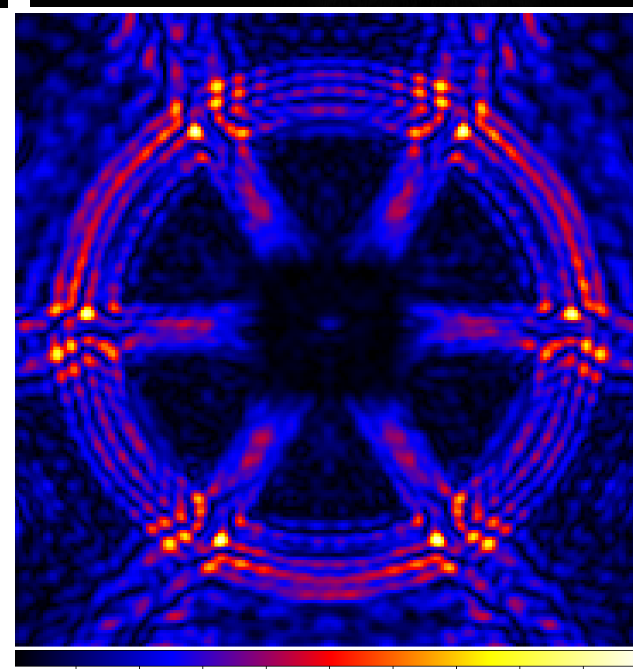
TMT coronagraph design for 1 l/D IWA





To be updated with new pupil shape





PSF at 1600nm

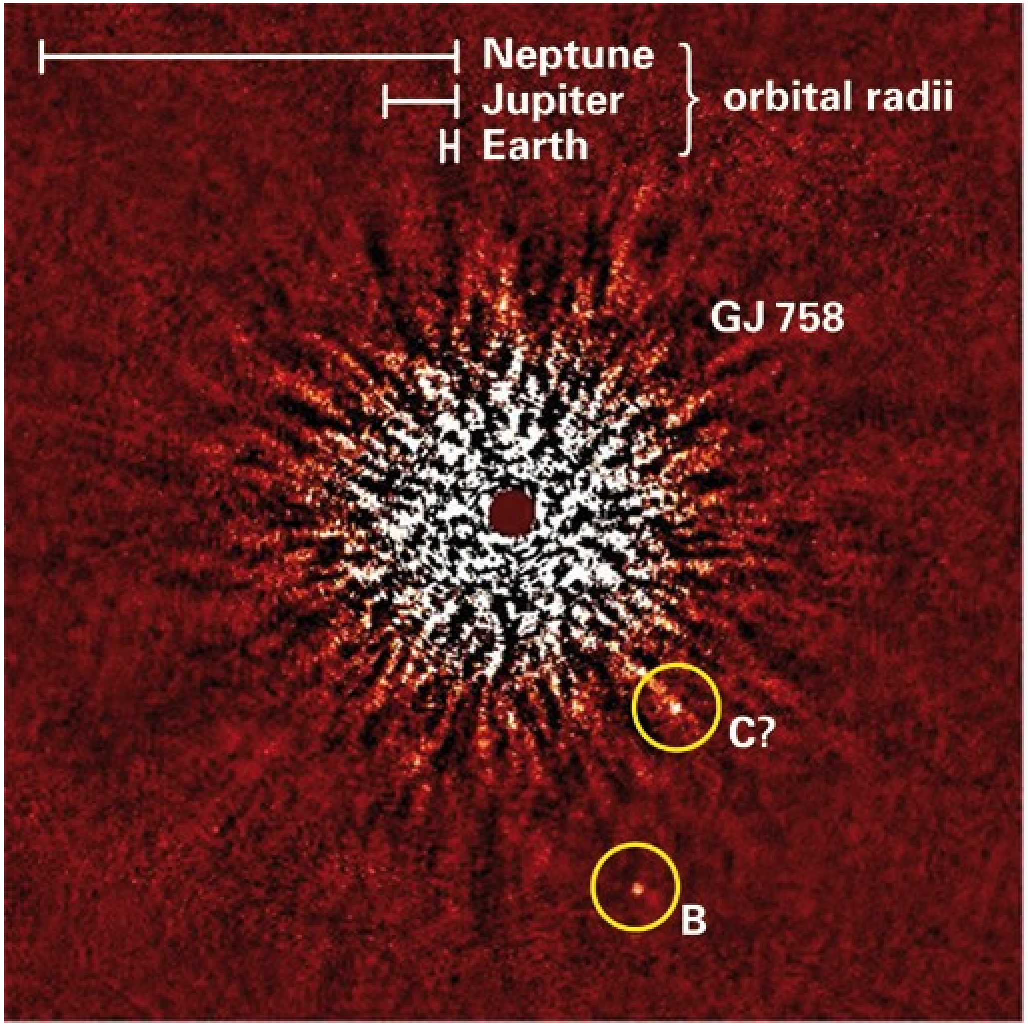
3e-9 contrast in 1.2 to 8 l/D

80% off-axis throughput

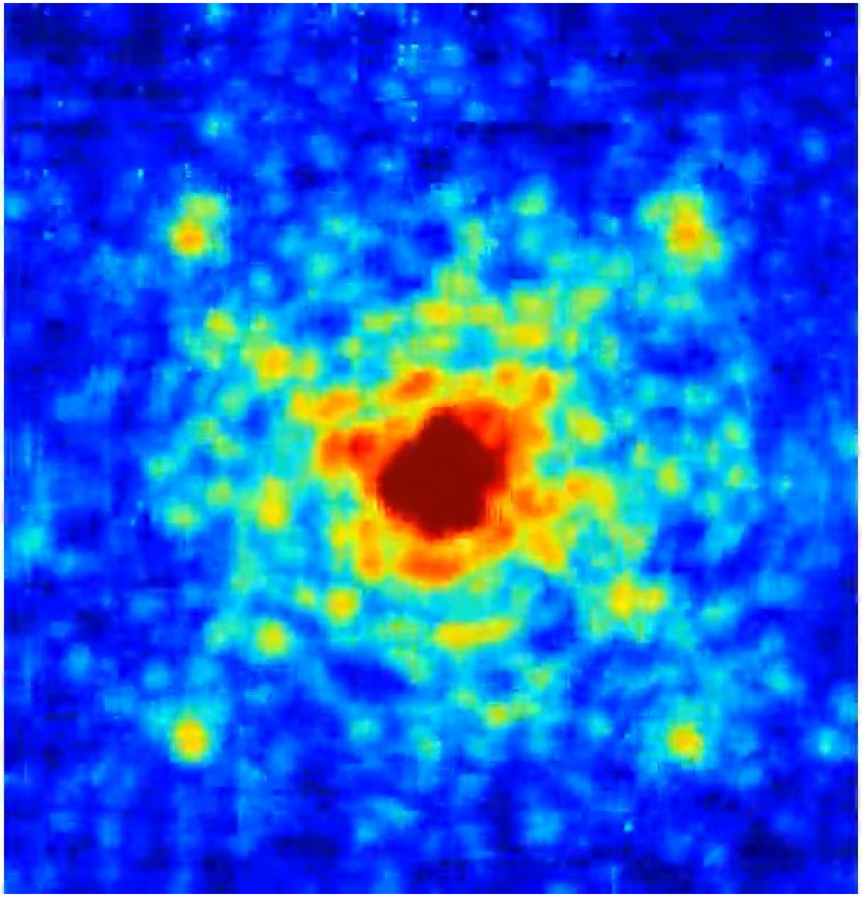
1.2 l/D IWA

CaF2 lenses SiO2 mask

The REAL challenge: Wavefront error (speckles)

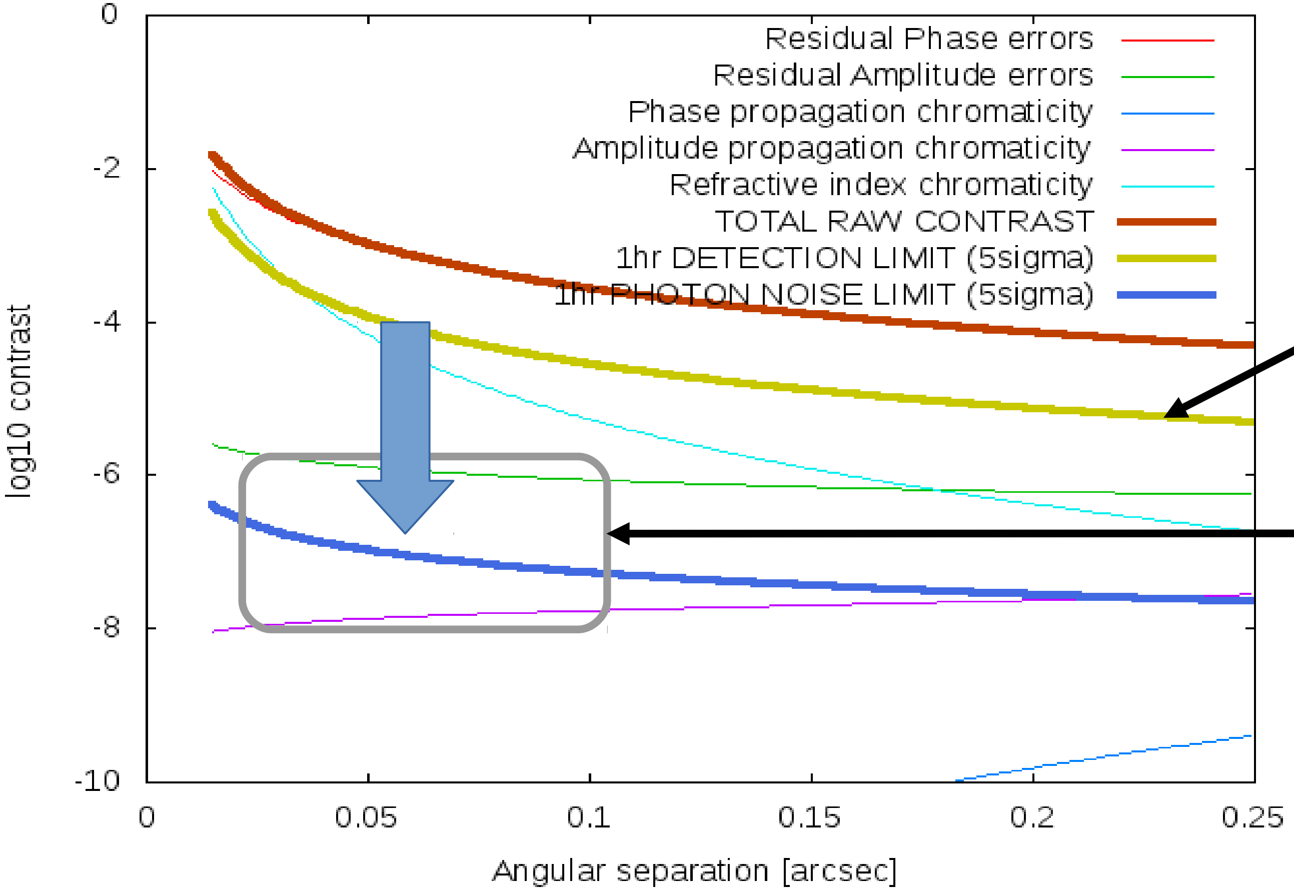


H-band fast frame imaging (1.6 kHz)



PREVIOUS technologies

30m: SH-based system, 15cm subapertures



Expected limit

Need <u>3 orders of magnitude</u> improvement in contrast to reach habitable planets

Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, **POOR AVERAGING due to crossing time**

Wavefront Control:
Key challenges

[1] WFS efficiency

M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires $(D/r0)^2$ times more light than diffraction-limited WFS
This is a **40,000x gain for 30m telescope** (assuming r0=15cm) → 11.5 mag gain

[2] Low latency WFC

System lag is extremely problematic → creates “ghost” slow speckles that last crossing time
Need ~200us latency (10 kHz system, or slower system + lag compensation), or multiple loops

[3] WF chromaticity

Wavefront chromaticity is a serious concern when working at ~1e-8 contrast
Visible light (~0.6 – 0.8 um) photon carry most of the WF information, but science is in near-IR

[4] Non-common path errors

It doesn't take much to create a 1e-8 speckle !

[5] PSF calibration

What is a speckle, what is a planet ?

Wavefront Control:
… and solutions

[1] Diffraction-limited pupil-plane WFS
Low or no modulation PyWFS is diffraction-limited
This is a **40,000x gain for 30m telescope** (assuming r0=15cm) → 11.5 mag gain

[2] Fast WFC loop
Fast hardware (Cameras, GPUs) can now run loop at ~5 kHz on ELT
Example: SCExAO runs 2000 actuators, 14,400 sensors at 3.5kHz using ~10% of available RTS computing power

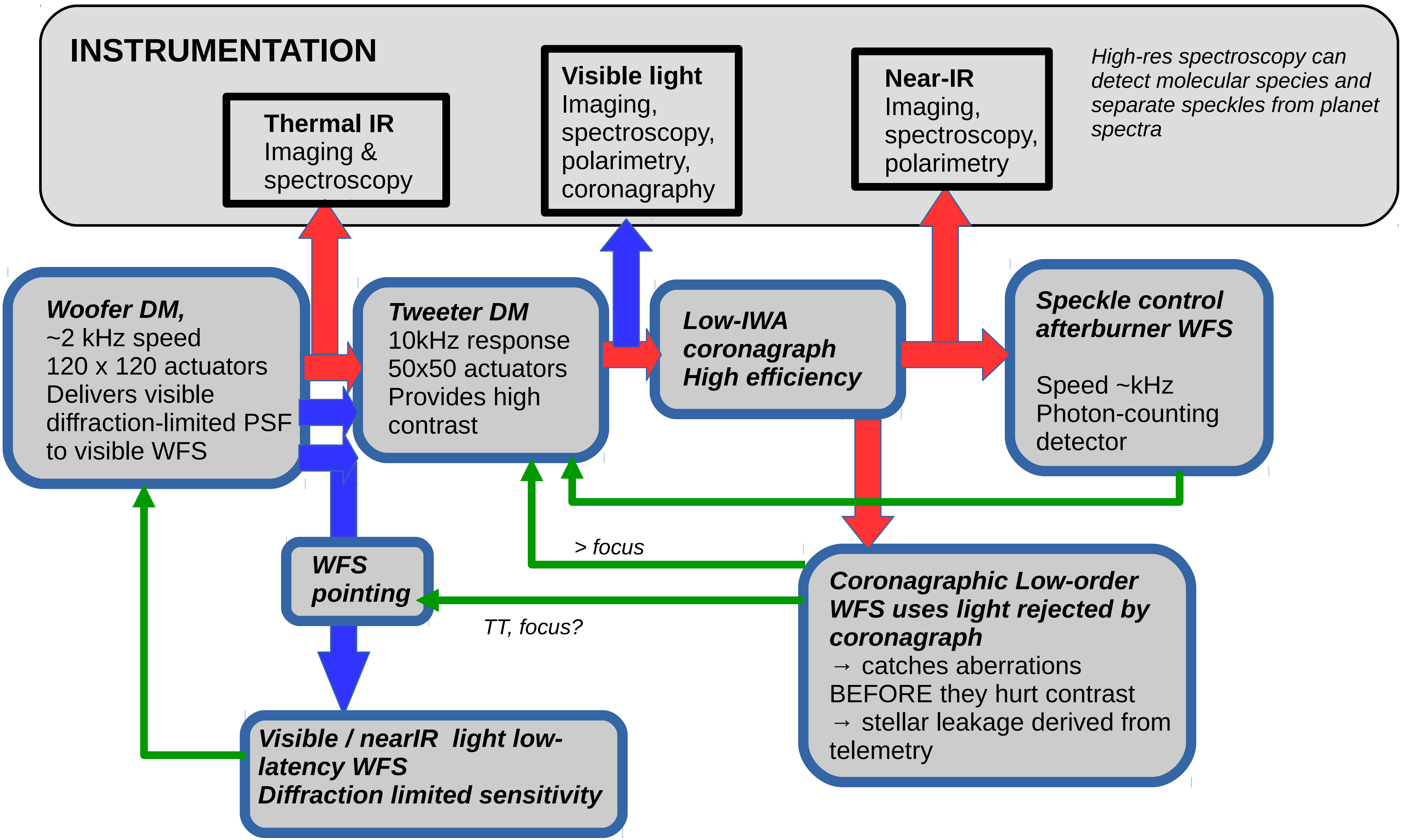
[1][2] Predictive Control
Eliminates time lag, improves sensitivity

[1][2][3][4][5] Fast speckle control, enabled by new detector technologies
Addresses simultaneously non-common path errors, (most of) lag error, chromaticity, and calibration

[5] Real-time telemetry → PSF calibration
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing

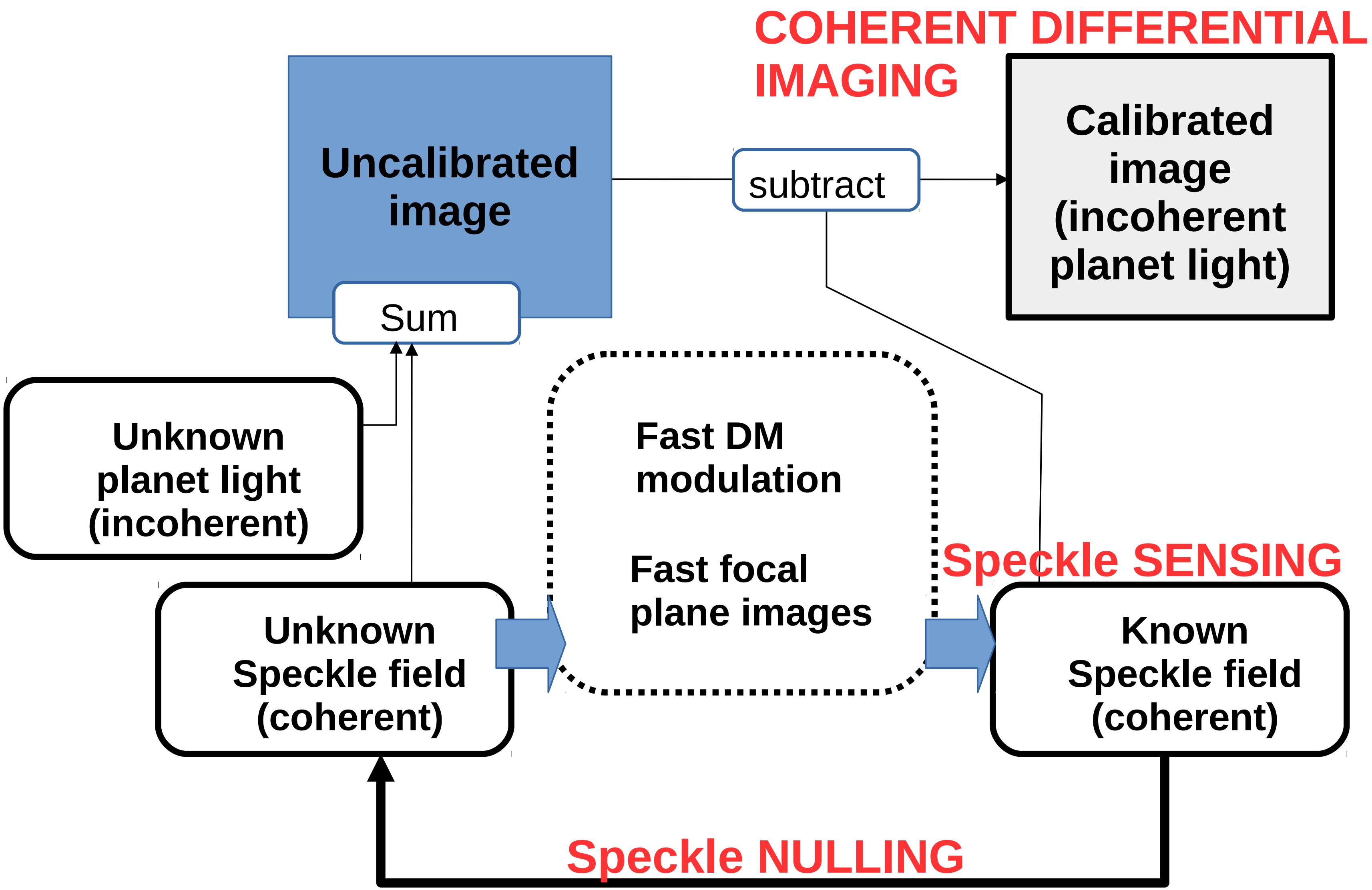
[5] Spectral discrimination
Especially powerful at high spectral resolution

Nominal ELT ExAO system architecture

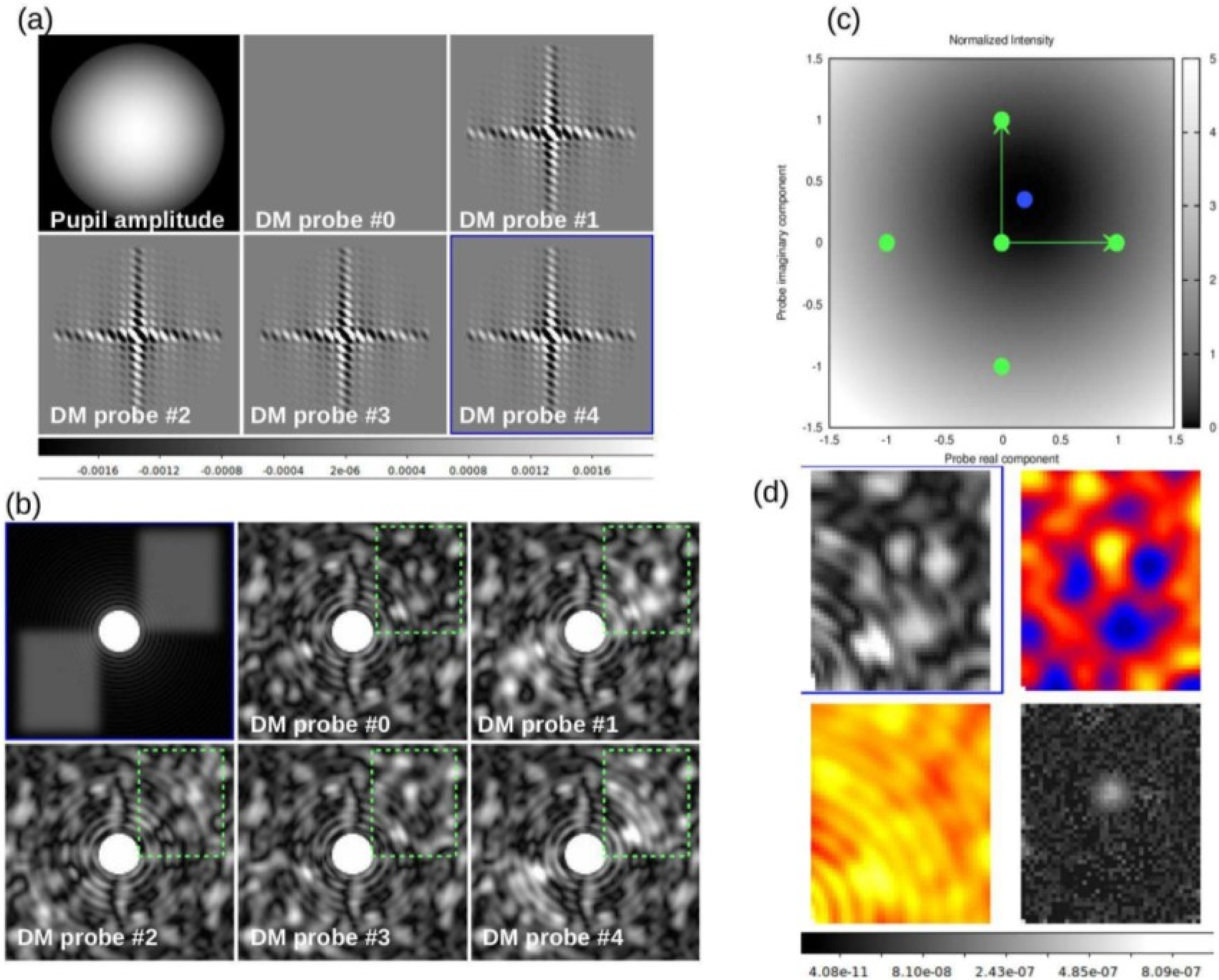


High Speed Speckle Control

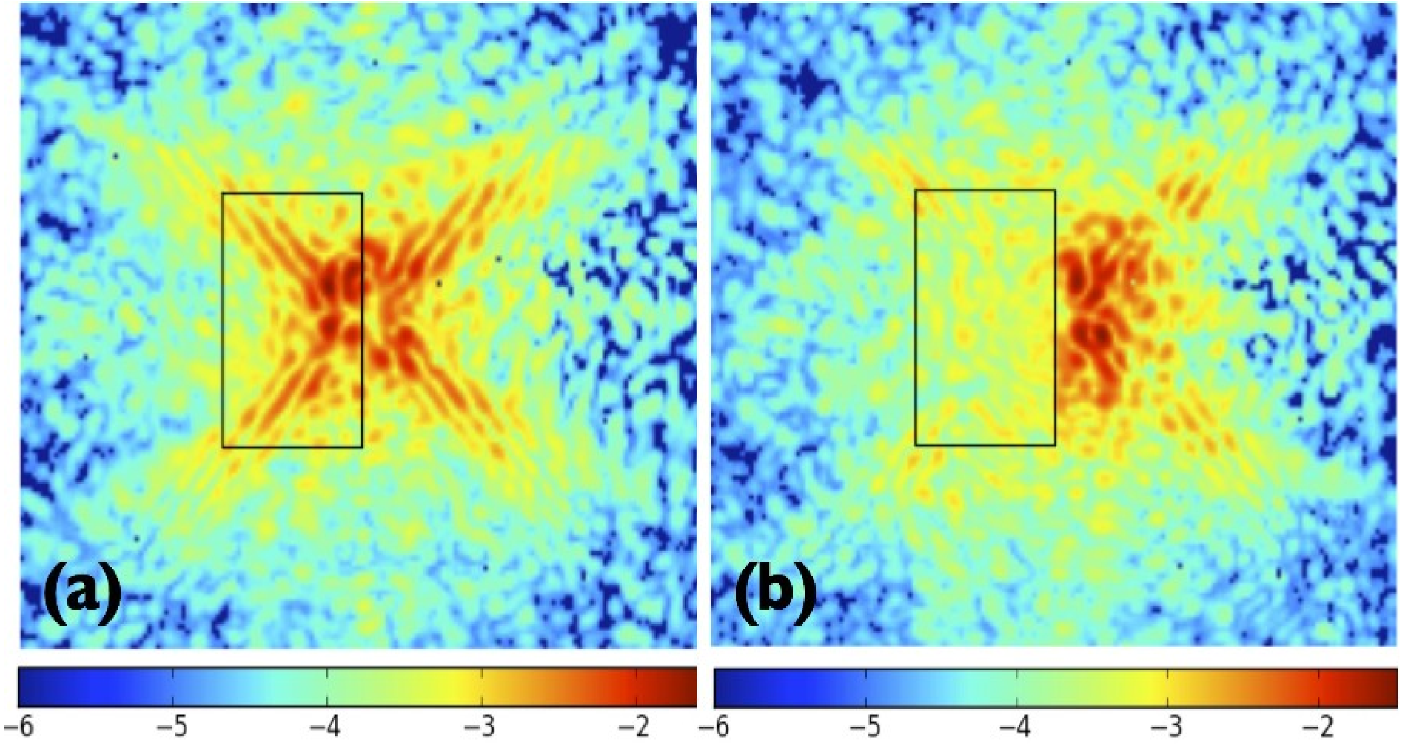
Main SCExAO upgrade: High speed speckle control with MKIDs



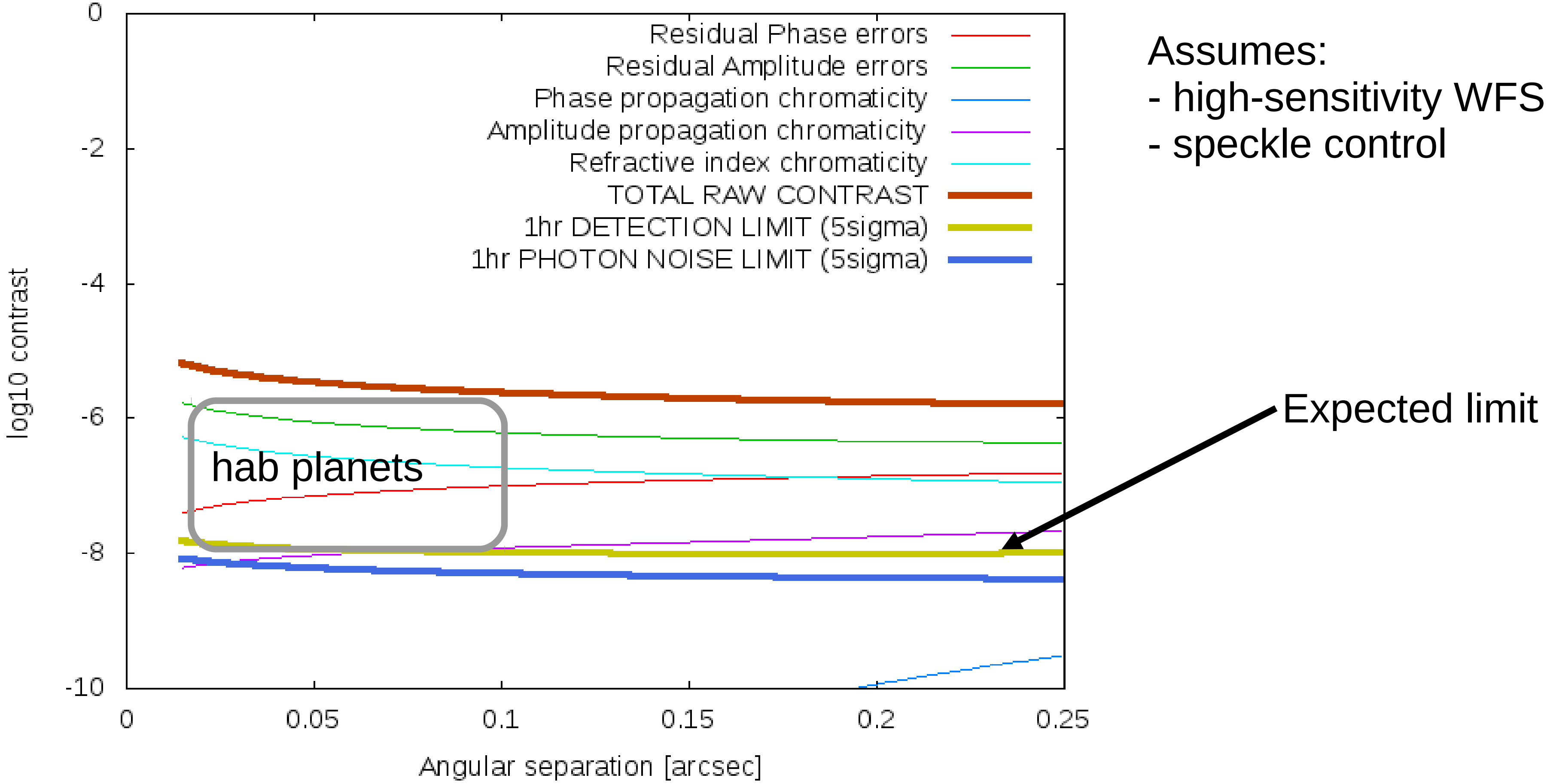
Coherent Speckle Differential Imaging



Speckle control
→ remove speckles in ½ field dark hole



CURRENT/NEW technologies



Assumes:
- high-sensitivity WFS
- speckle control

300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

Predictive control → 100x contrast gain ?

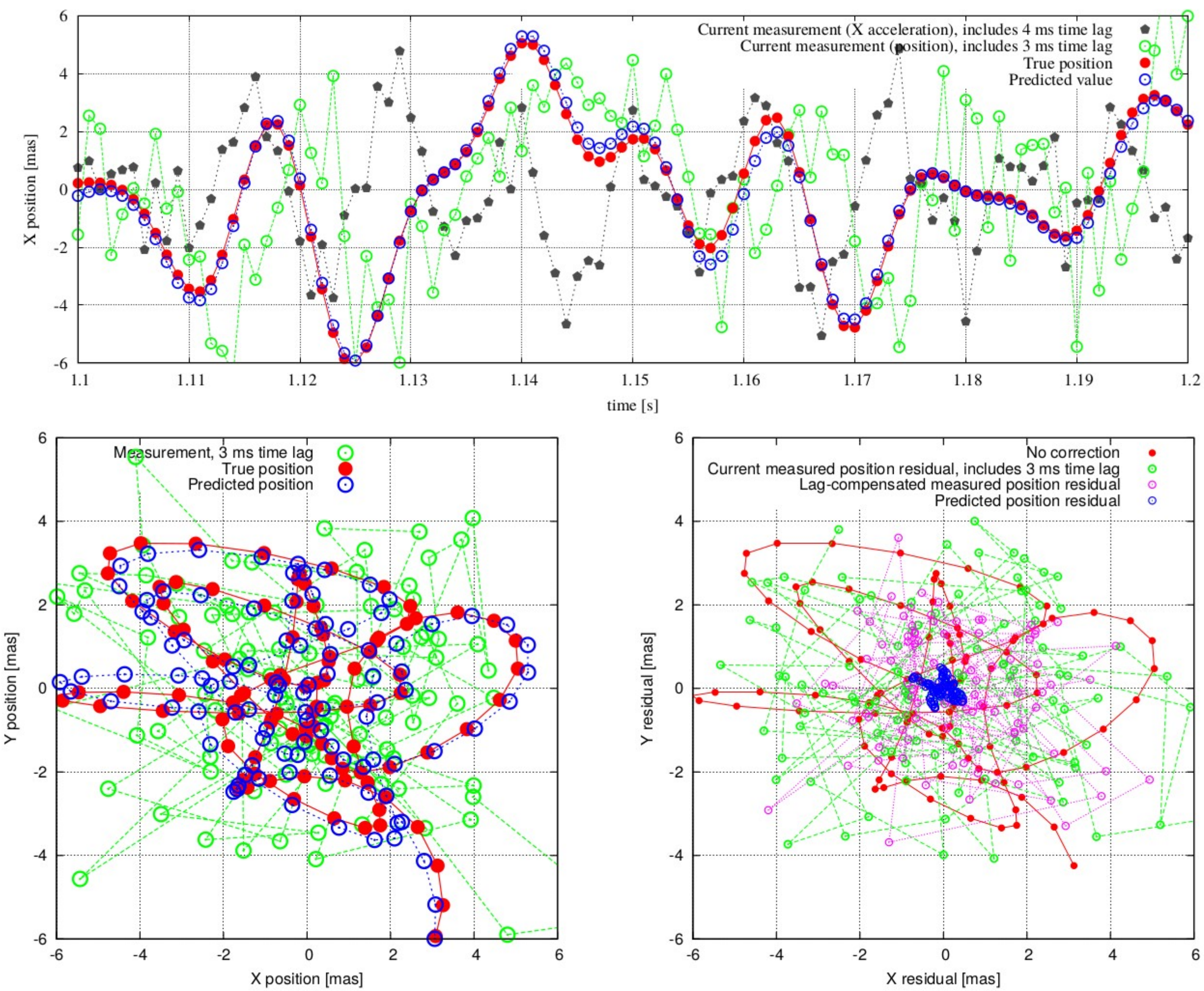
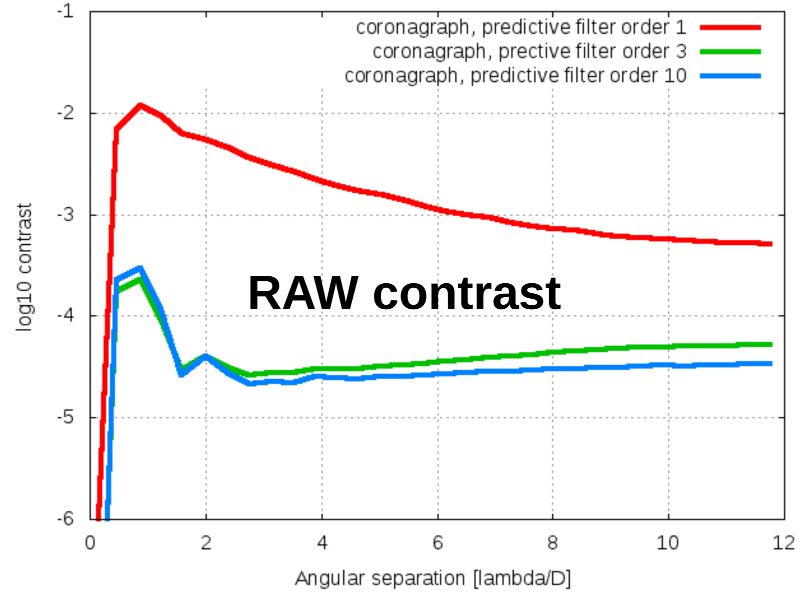
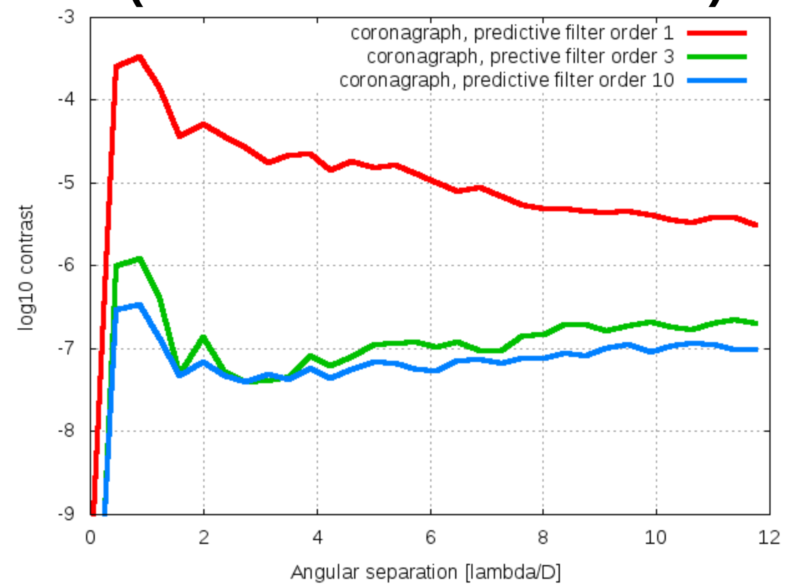


FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.



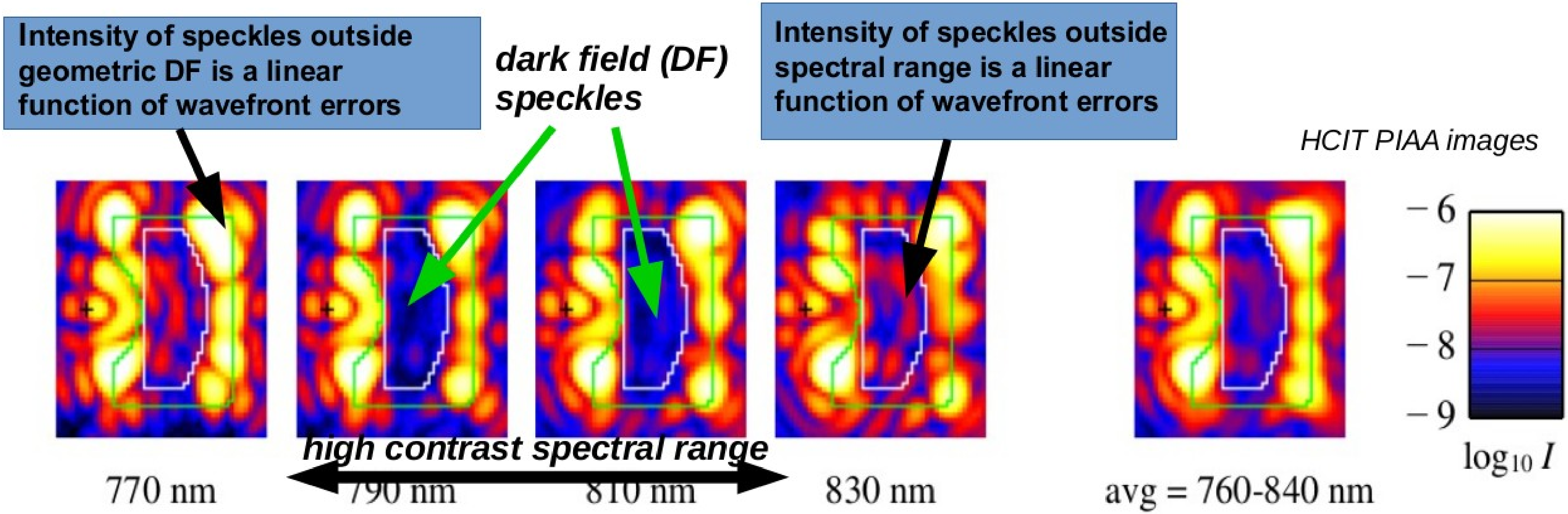
1hr detection limit (PSF subtraction residual)



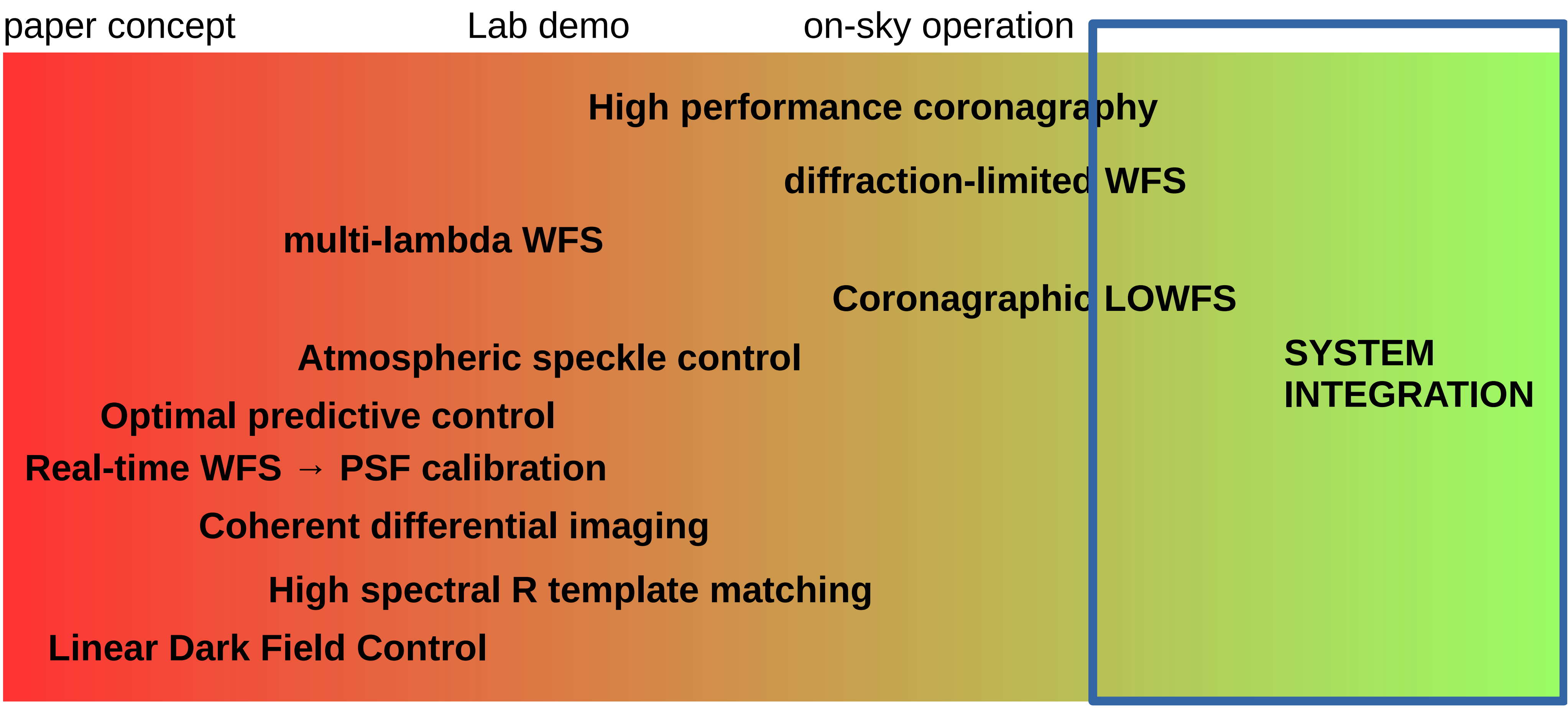
Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



Key technologies need rapid maturation from paper concepts to system integration



Subaru Coronagraphic Extreme Adaptive Optics

- **Flexible** high contrast imaging platform
- Meant to **evolve to TMT instrument** and validate key technologies required for direct imaging and spectroscopy of habitable exoplanets

Core system funded by Japan
Modules/instruments funded by Japan + international partners:
- IFS funded by Japan, built by Princeton Univ
- MKIDs funded by Japan, built by UCSC
- SAPHIRA camera provided by UH
- VAMPIRES instrument funded and built by Australia
- FIRST instrument funded and built by Europe

SCExAO is an international platform to prepare ELT imaging of habitable planets around M-type stars

Modules

Subaru Coronagraphic Extreme Adaptive Optics

The wavefront control feeds a high Strehl PSF to various modules, from 600 nm to K band.

Visible (600 – 950 nm):

VAMPIRES, non-redundant masking, polarimetry, with spectral differential imaging capability (h-alpha, SII)

FIRST, non-redundant remapping interferometer, with spectroscopic analysis

RHEA, single mode fiber injection, high-res spectroscopy, high-spatial resolution on resolved stars

IR (950-2400 nm):

HiCIAO - high contrast image (y to K-band)

SAPHIRA - high-speed photon counting imager, (H-band for now)

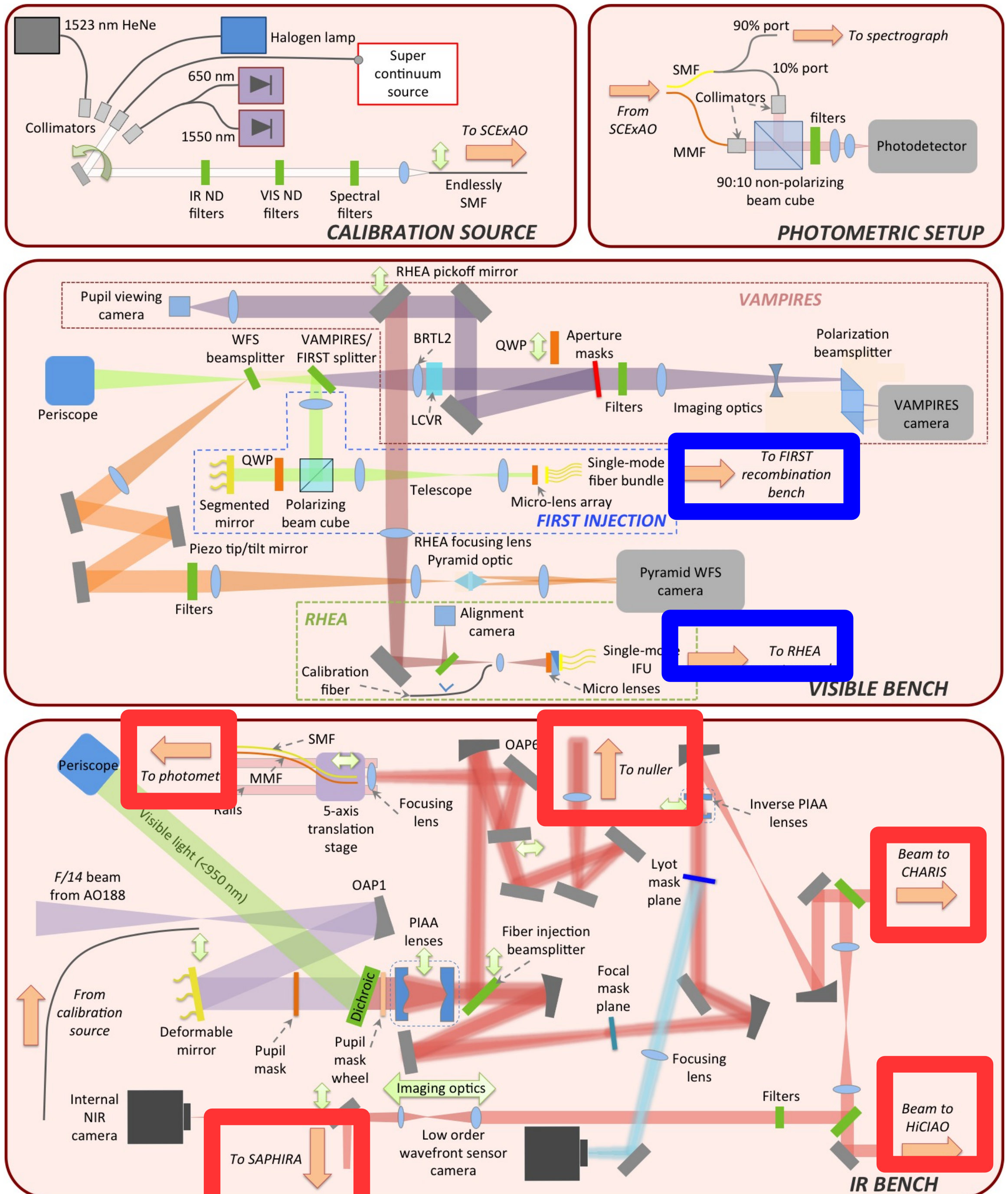
CHARIS - IFS (J to K-band)

MEC - MKIDs detector, high-speed, energy discriminating photon counting imager (y to J-band)

NIR single mode injection, high throughput high resolution spectroscopy. Soon will be connected to the new IRD

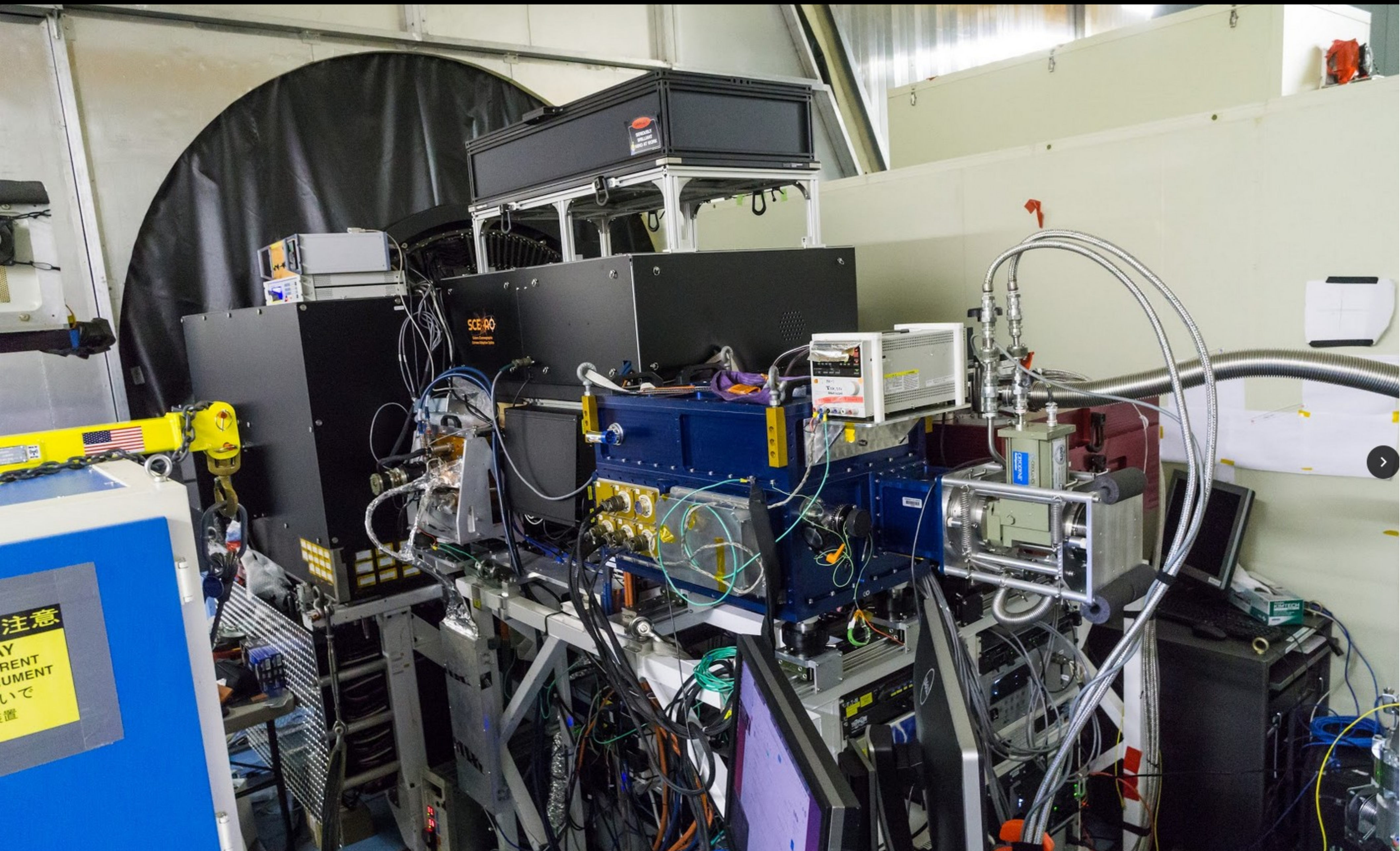
Various small IWA (1-3 l/D) coronagraphs for high contrast imaging – PIAA, vector vortex, 8OPM

GLINT - NIR nulling interferometer based on photonics



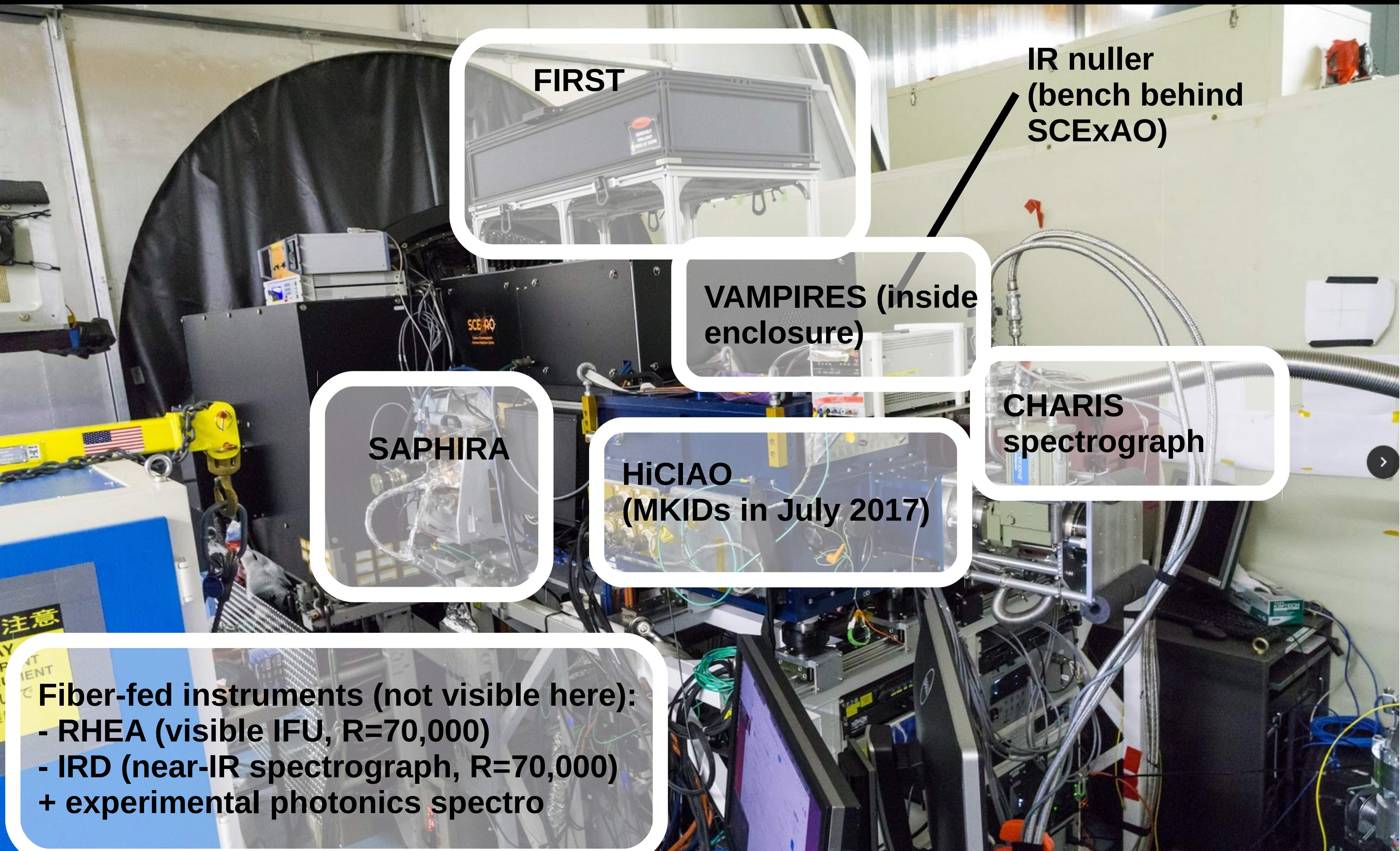
Jovanovic et al, PASP, 127, 890 (2015)

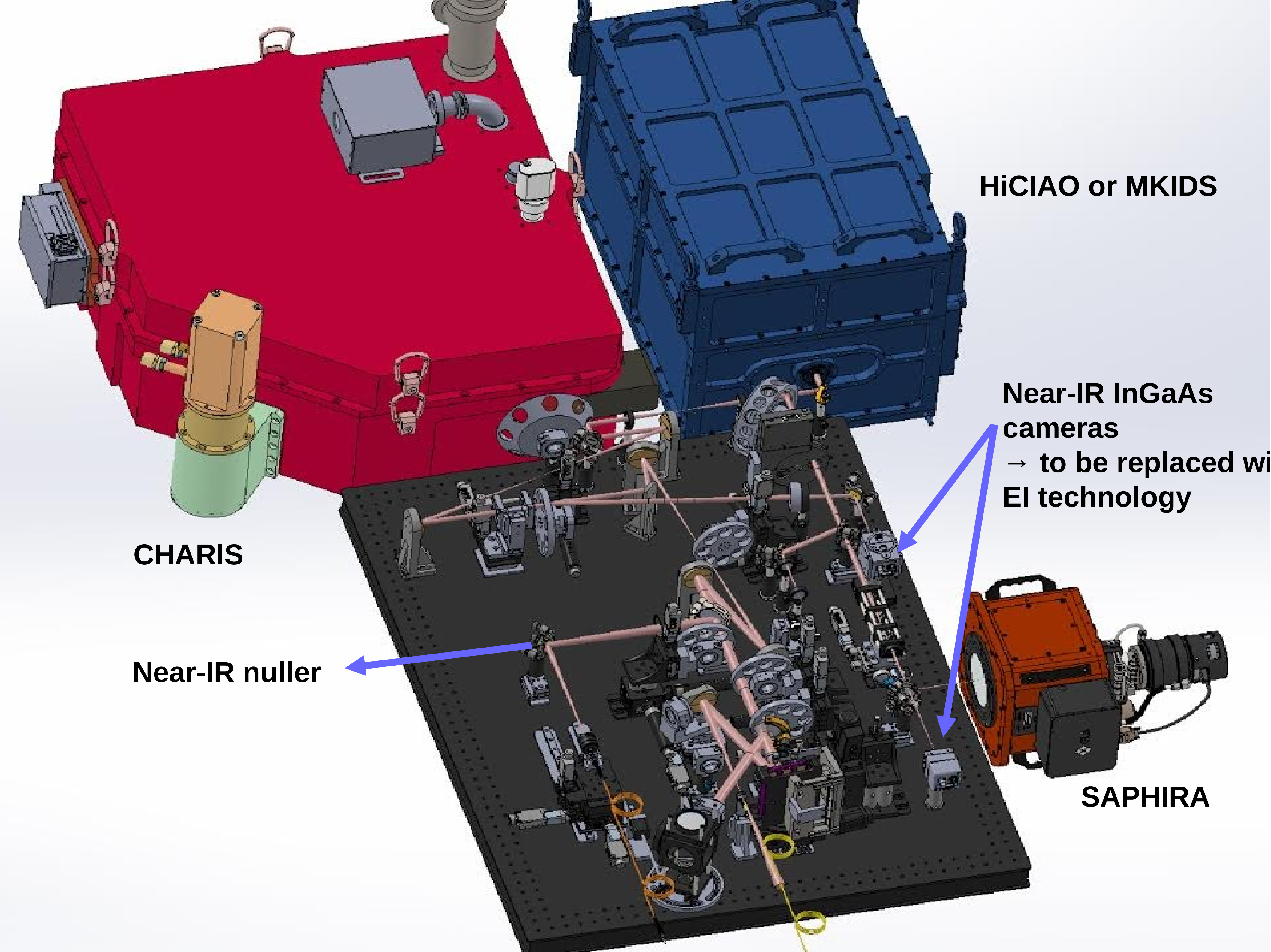
Subaru Coronagraphic Extreme Adaptive Optics



SCExAO

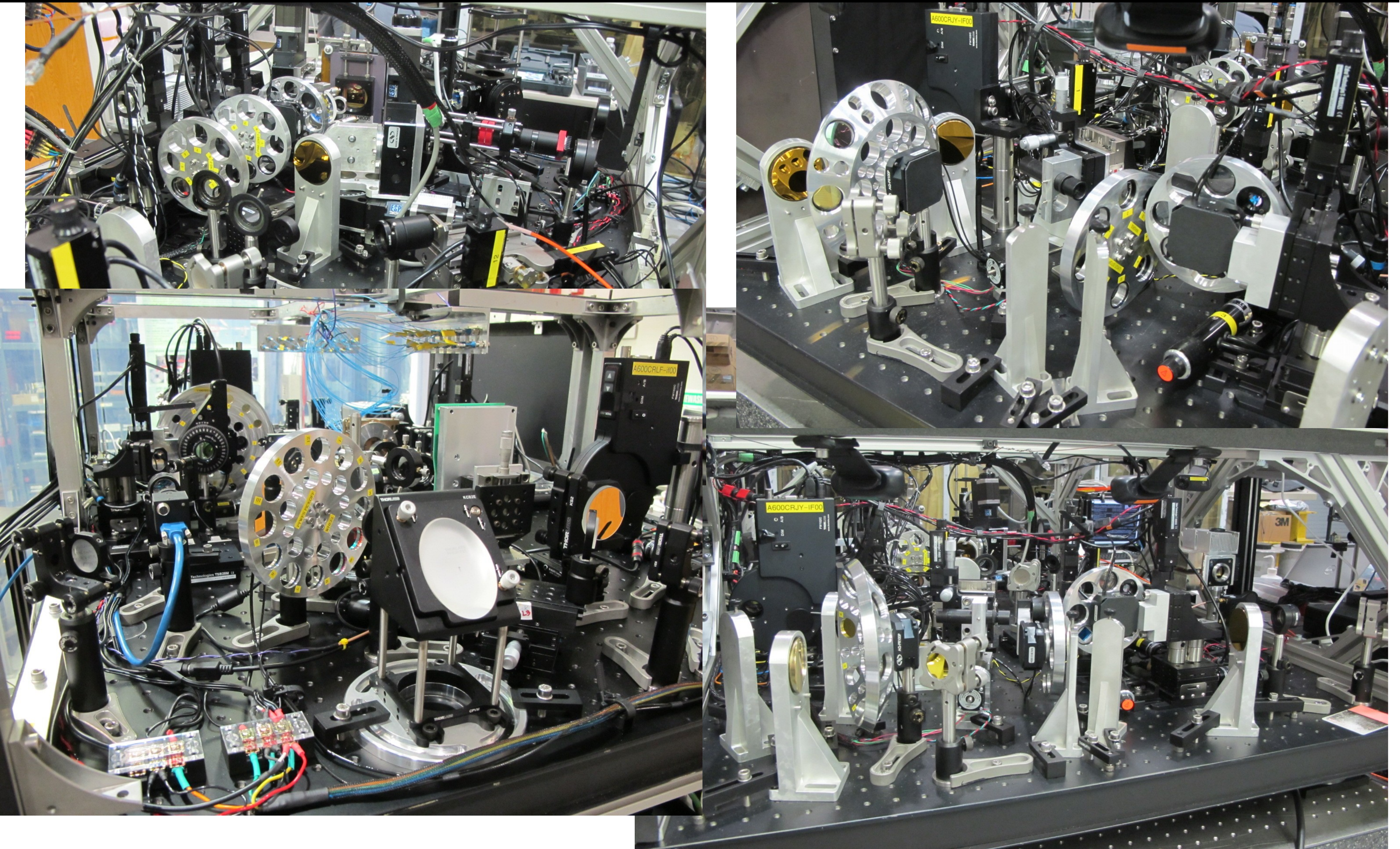
Subaru Coronagraphic Extreme Adaptive Optics



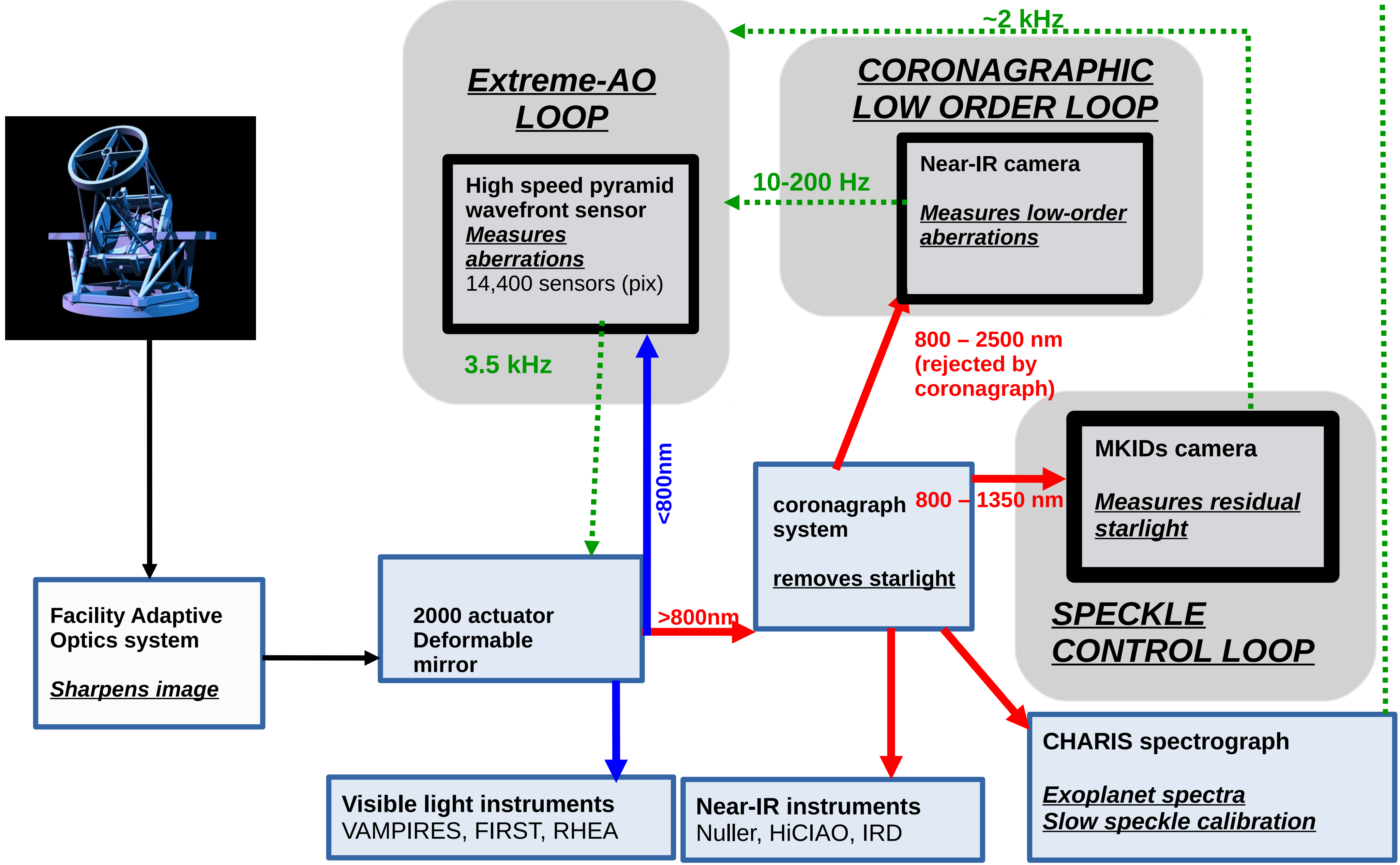

HiCIAO or MKIDS
Near-IR InGaAs cameras
→ to be replaced wi
EI technology
CHARIS
Near-IR nuller
SAPHIRA

SCExAO

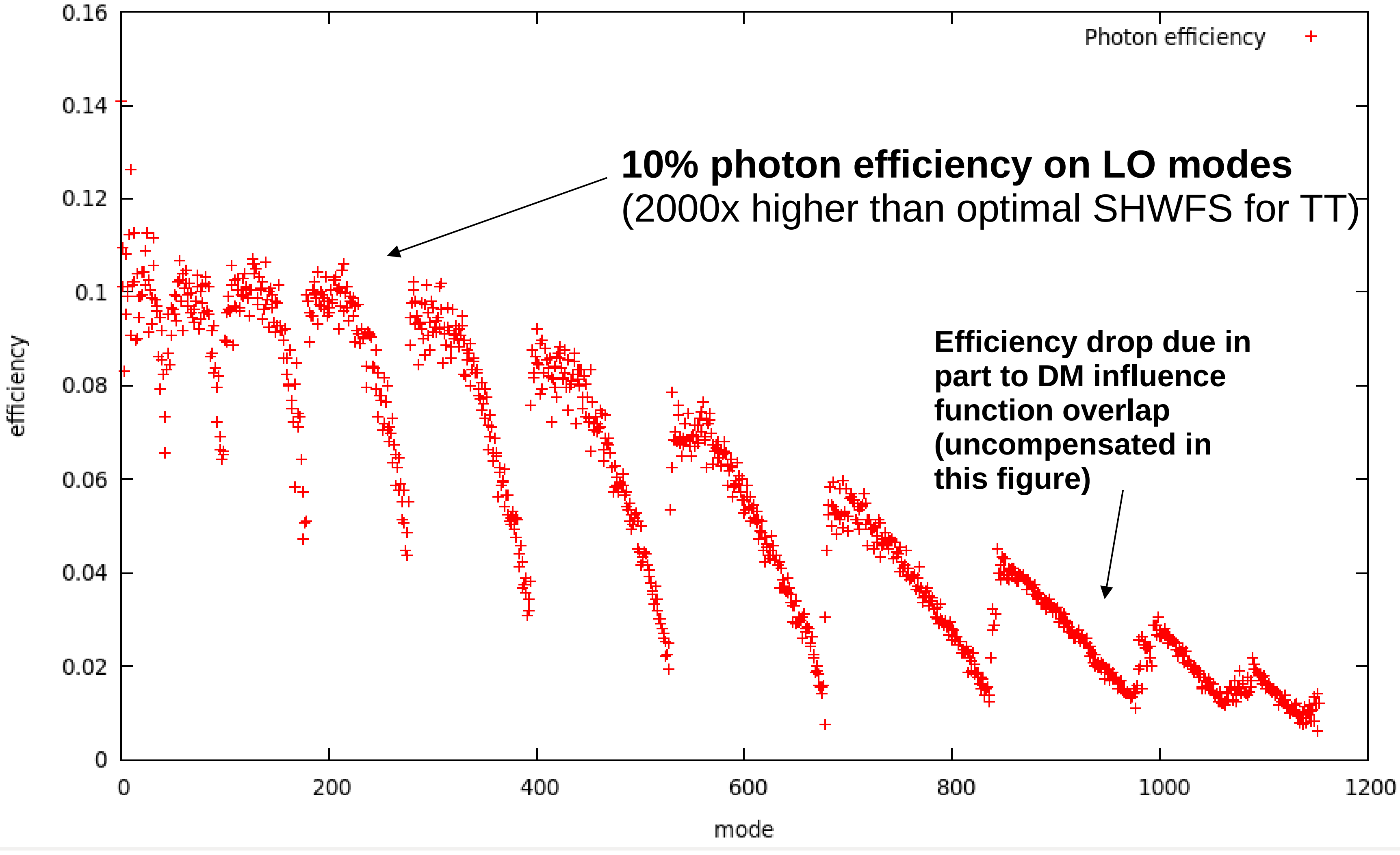
Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics



Measured photon efficiency (SCExAO, sub-l/D modulation pyramid)

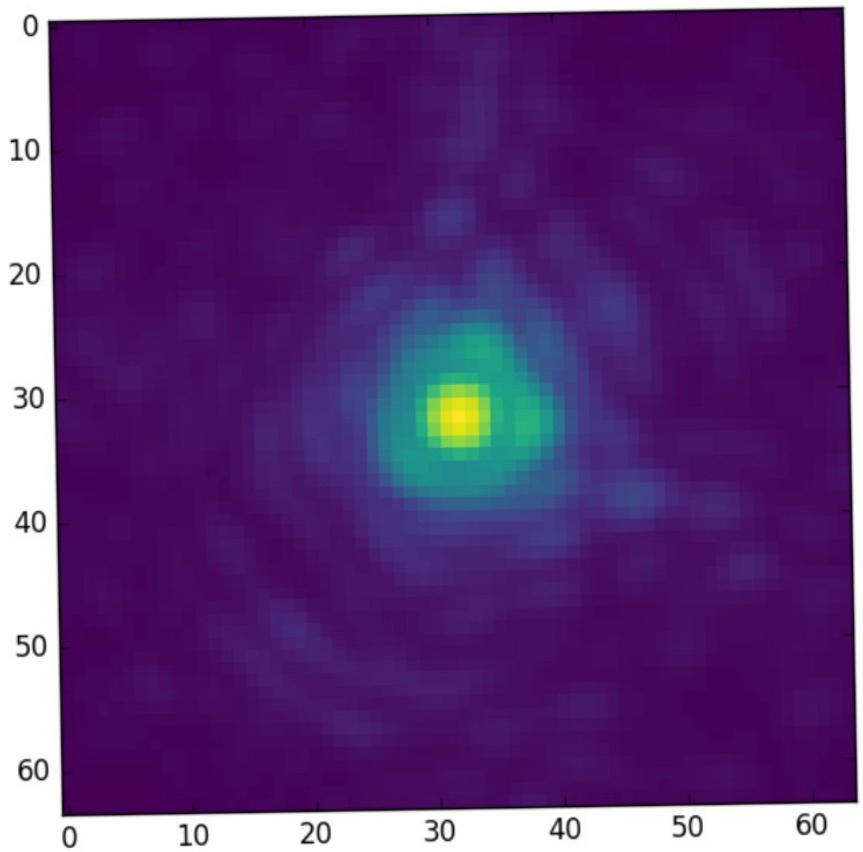


Preliminary VAMPIRES science

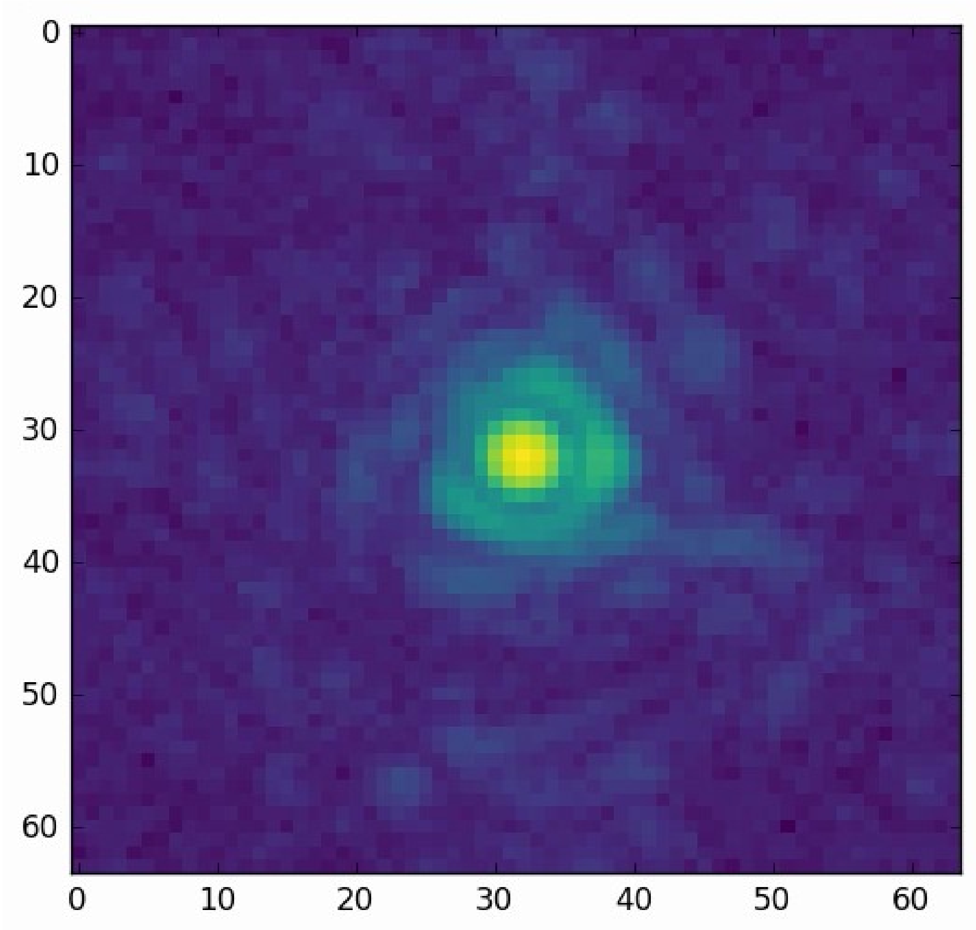
Diffraction-limited imaging in visible light

750nm, 1kHz imaging
log scale

Summed image



Video



Preliminary VAMPIRES science

Circumstellar dust around Red Supergiant μ Cephei

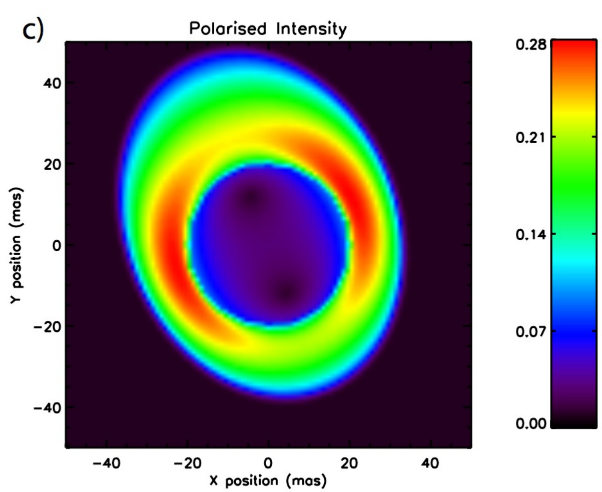
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

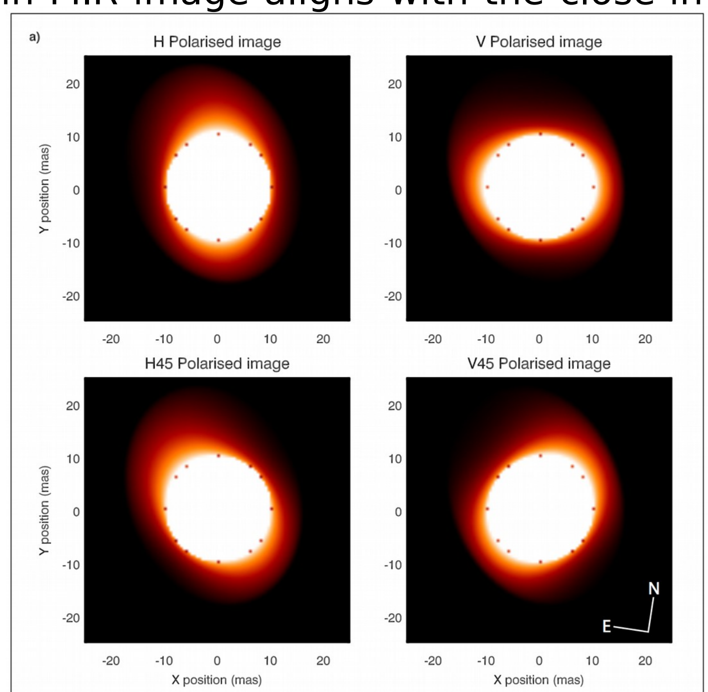
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

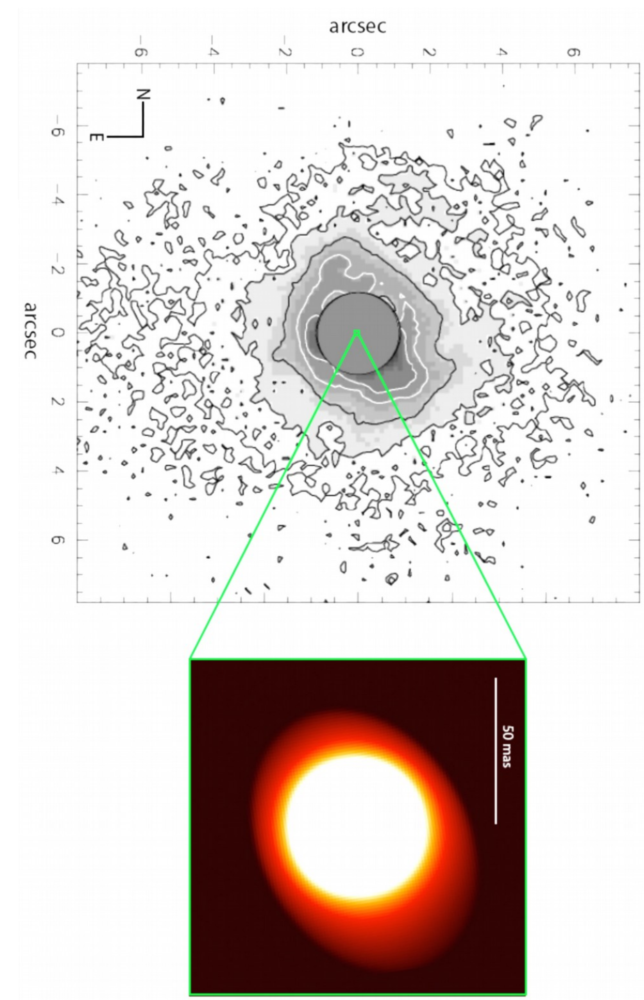
Scattered-light fraction: 0.081 ± 0.002

PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.



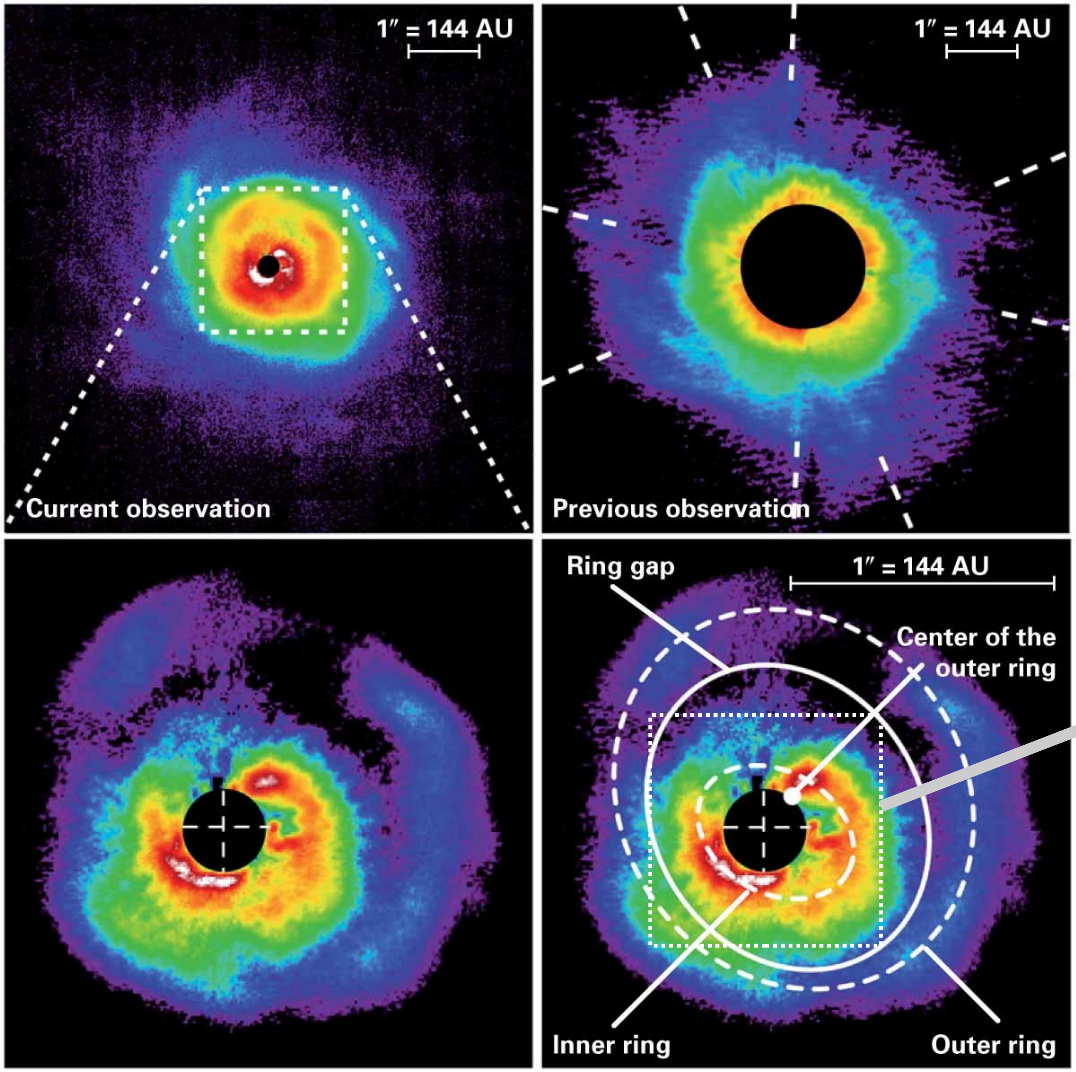




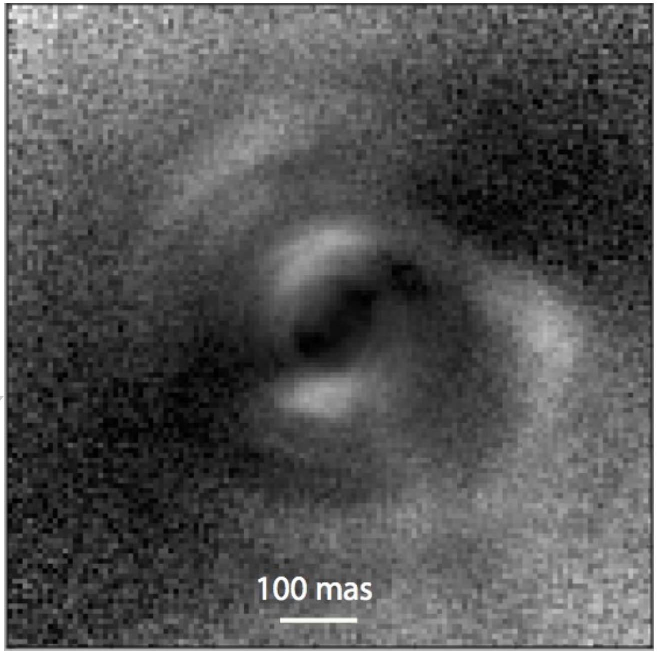
Preliminary VAMPIRES science

AB Aur star, polarimetric imaging mode

HiCIAO, near-IR

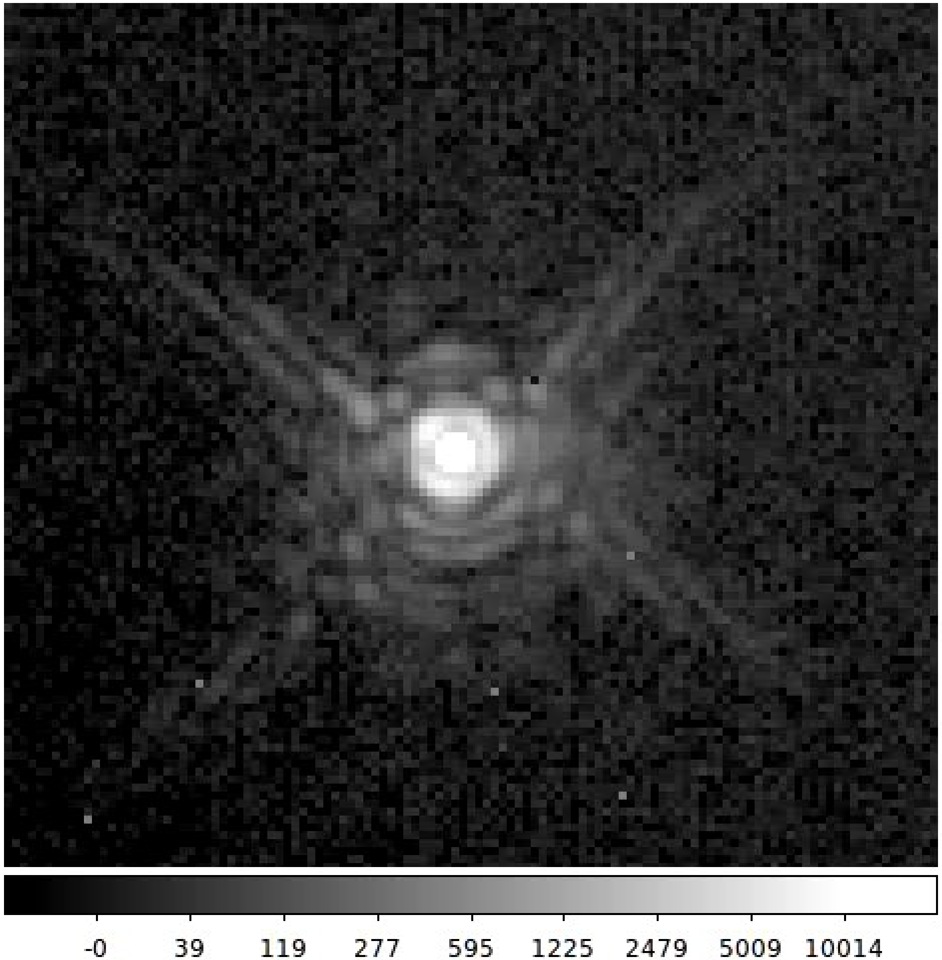


VAMPIRES
(preliminary data reduction)



Current PSF stability @ SCExAO

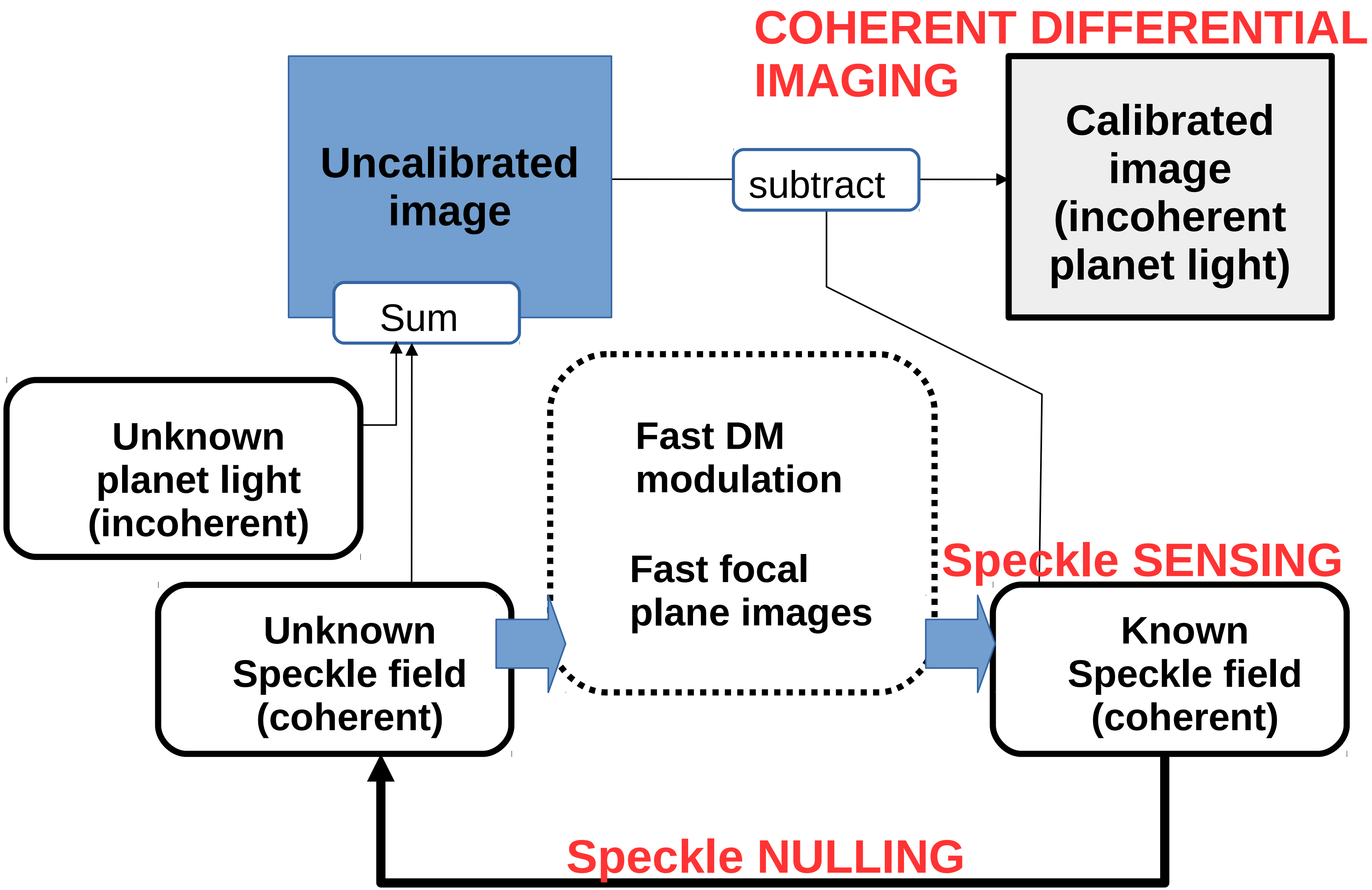
Highly stable PSF for coronagraphy
SCExAO provides sensing and correction at 3.5 kHz
14,400 pixel WFS → 2000 actuators



1630nm (SCExAO internal camera)
3 Hz sampling

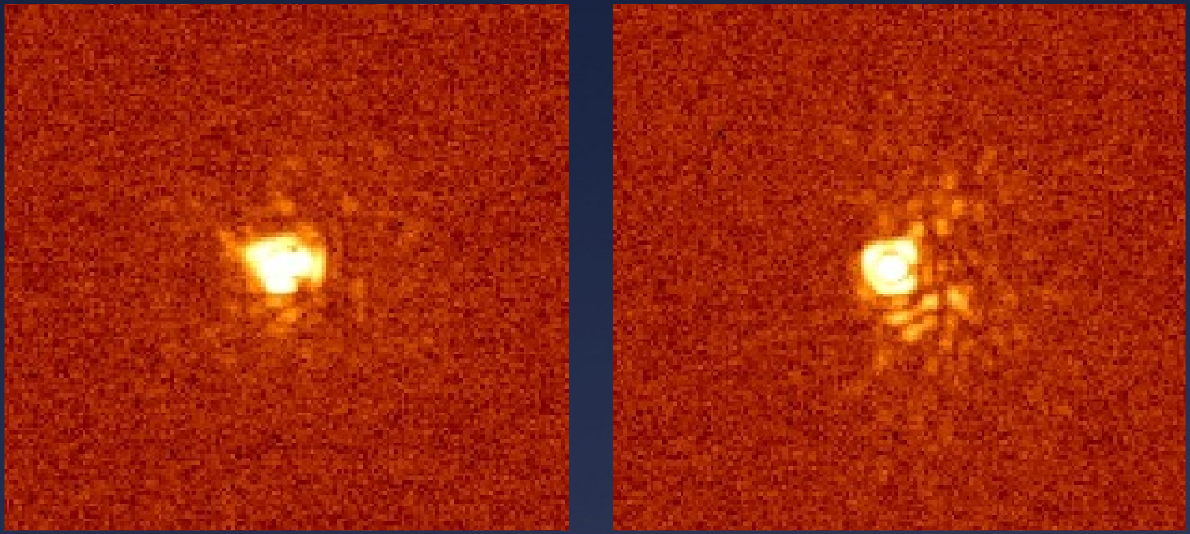
High Speed Speckle Control

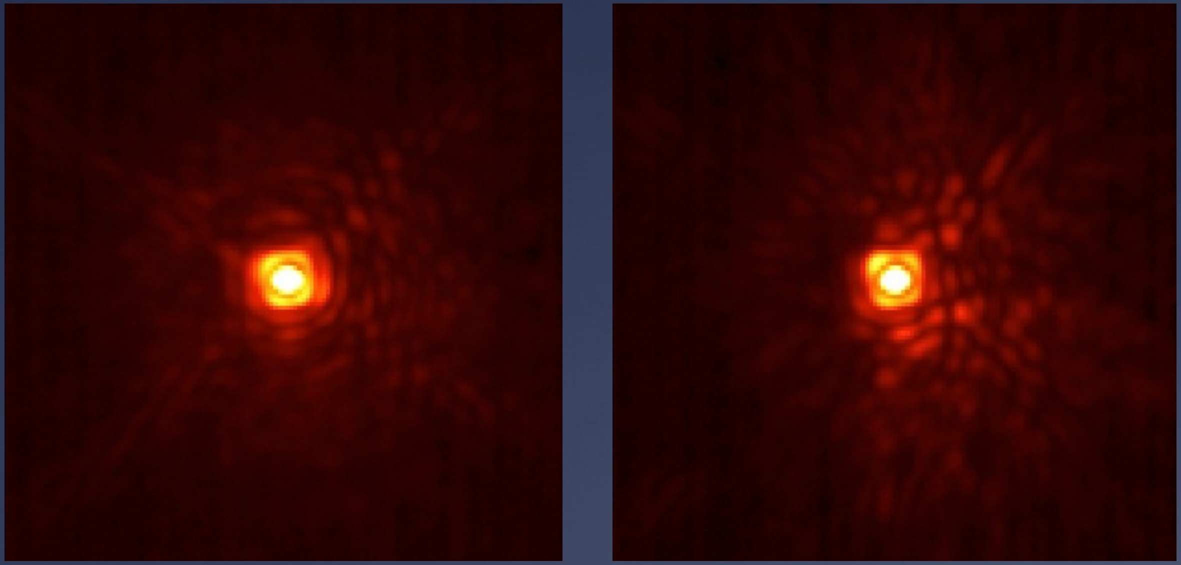
Main SCExAO upgrade: High speed speckle control with MKIDs



speckle nulling results on-sky (June 2014)

Single frames: 50 us

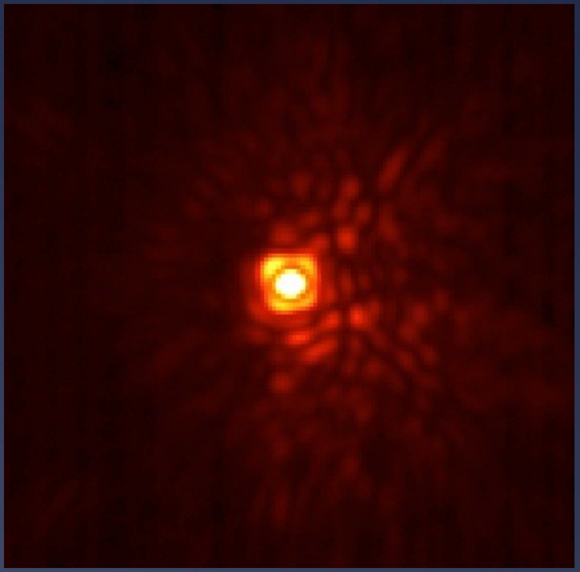




Sum of 5000 frames: shift and add

Meta data:

Date: 2nd or June
Target: RX Boo (also repeated on Vega)
Seeing: <0.6”
AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)
Coronagraph: None (used Vortex on Vega)

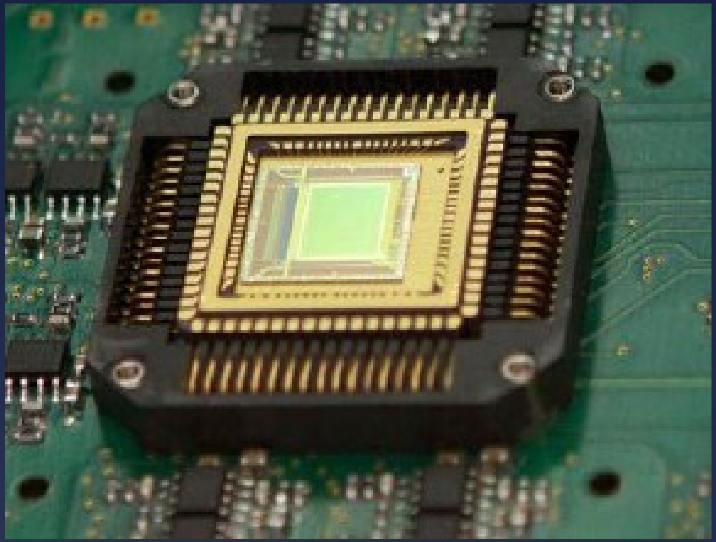


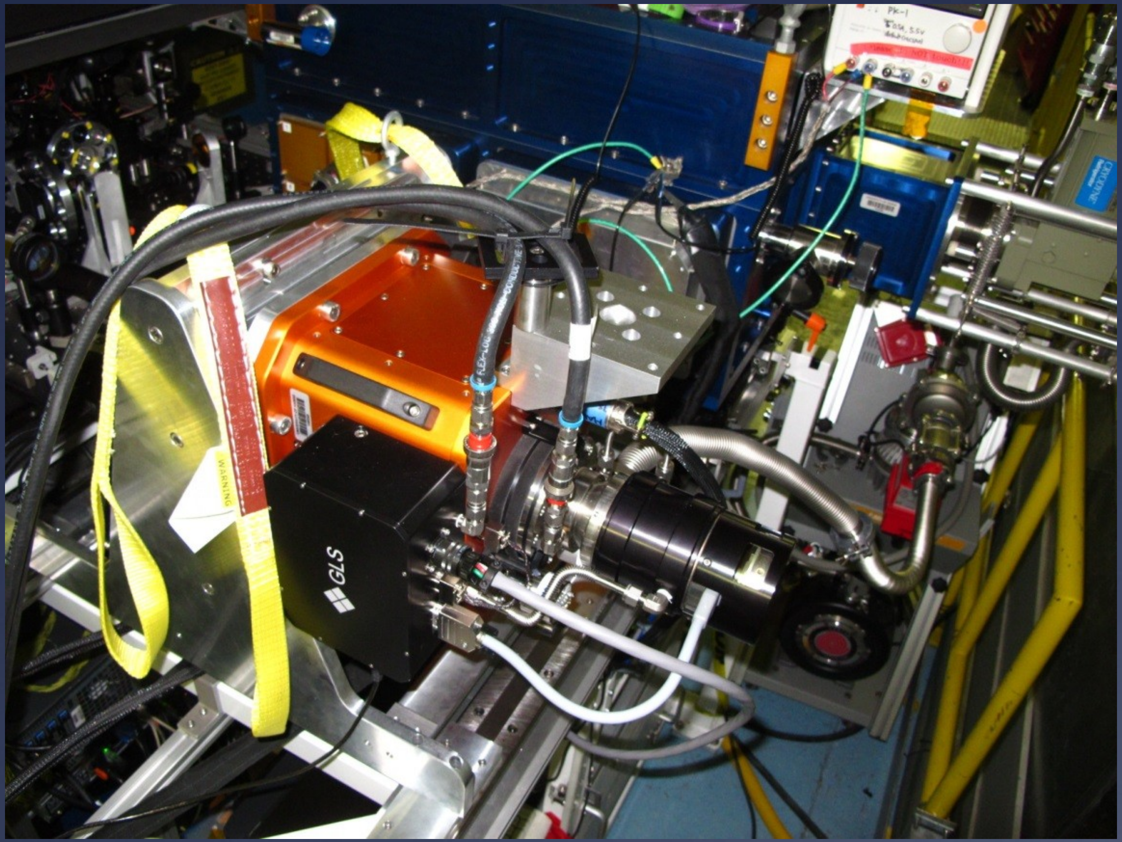
Martinache. et. al.

SAPHIRA Infrared APD array

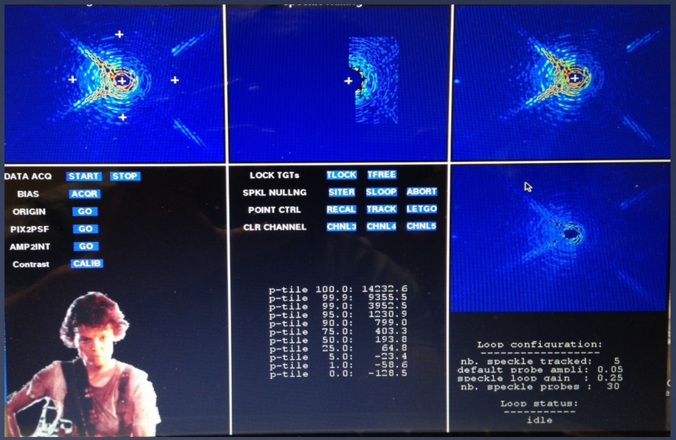
HgCdTe avalanche photodiode
manufactured by Selex

<u>Specifications</u>
320 x 256 x 24µm
32 outputs
5 MHz/Pix



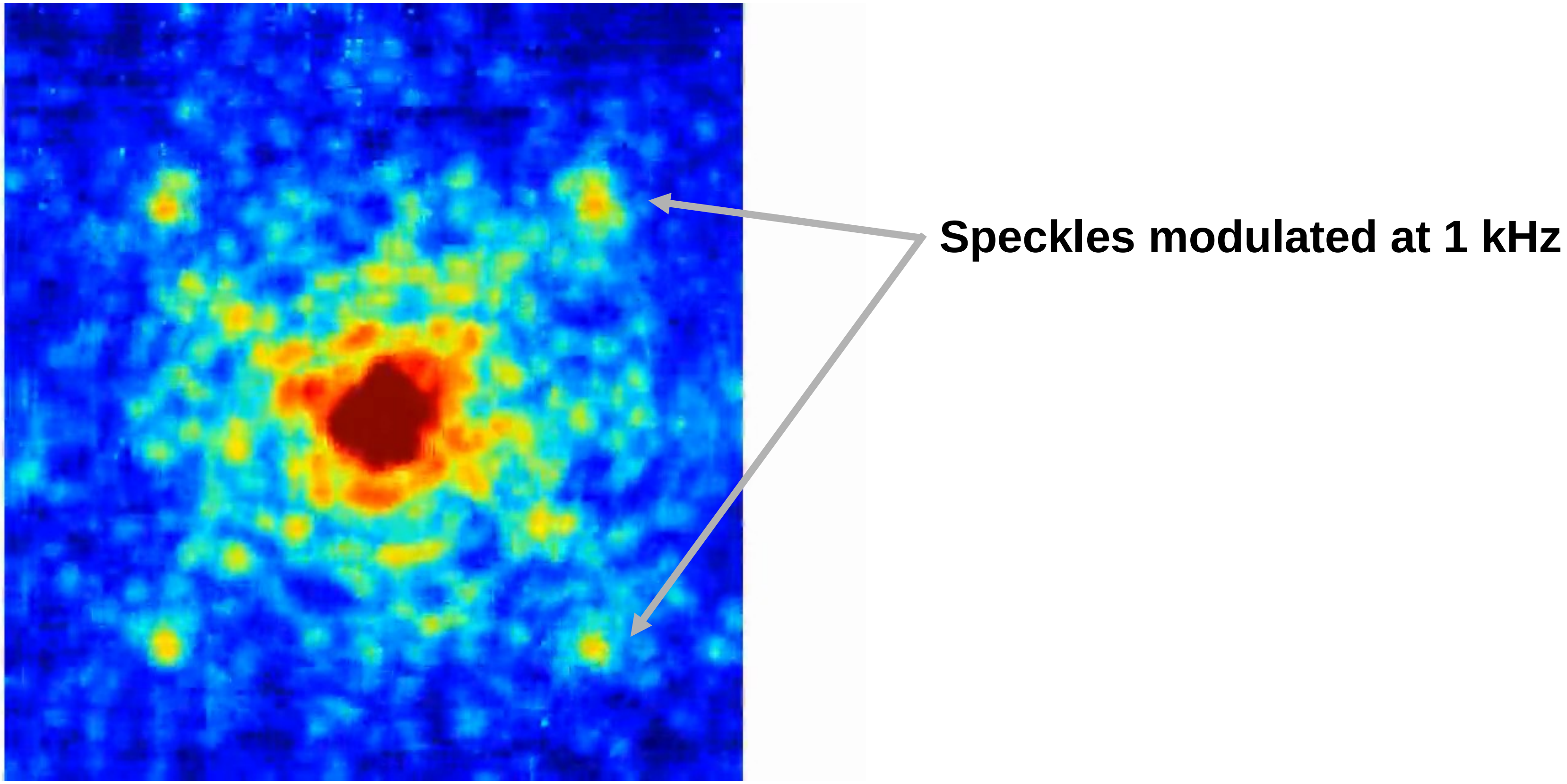


50 frame average

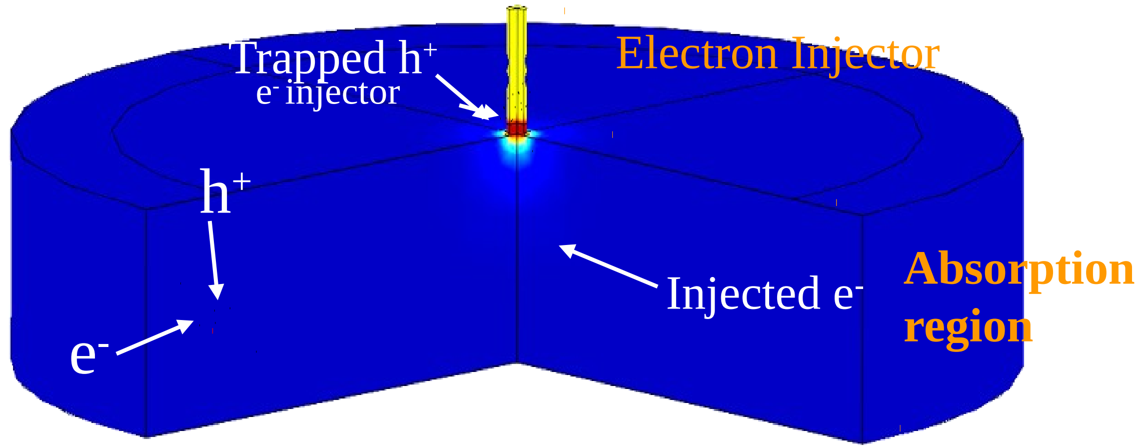


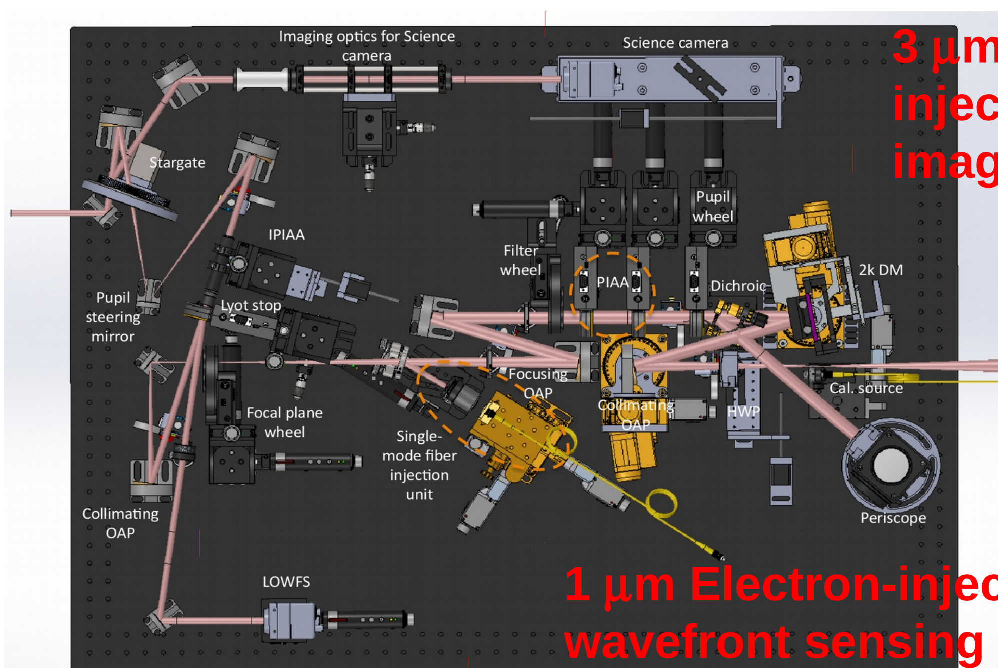
High speed speckle modulation

1.6 kHz frame rate, H-band
(played at 30 Hz)



Electron-injector nearIR camera (Northwestern Univ / Keck foundation)



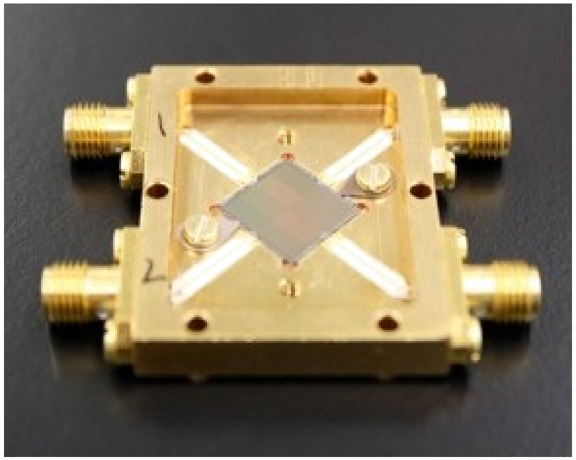


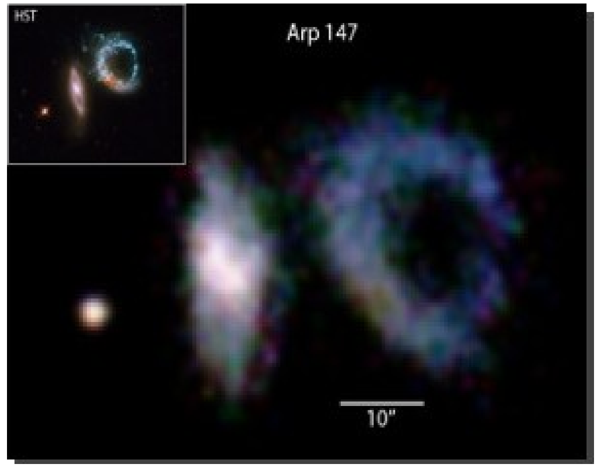
3 µm Electron-injection speckle imaging camera

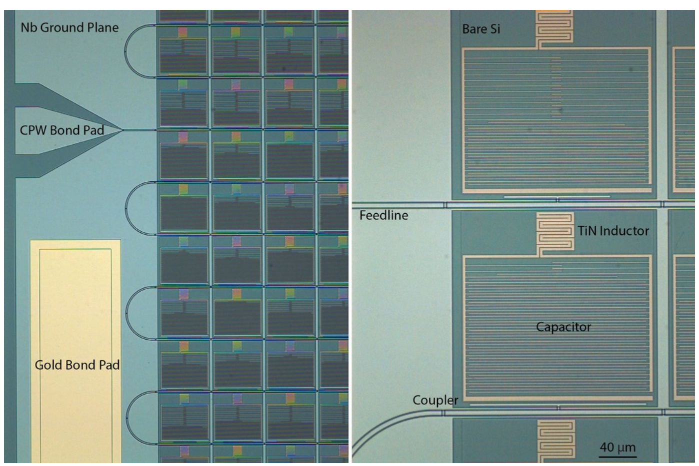
1 µm Electron-injection low-order wavefront sensing (pointing) camera

MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 140x140 pixel camera







Pixels are microwave resonators at ~100mK
photon hits → resonator frequency changes

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in CY2017

SCExAO@Subaru → TMT

Demonstrate and validate performance on Subaru prior to deployment on TMT

→Goal: **be ready to go as soon as telescope ready (visitor instrument ?)**, with well understood instrument

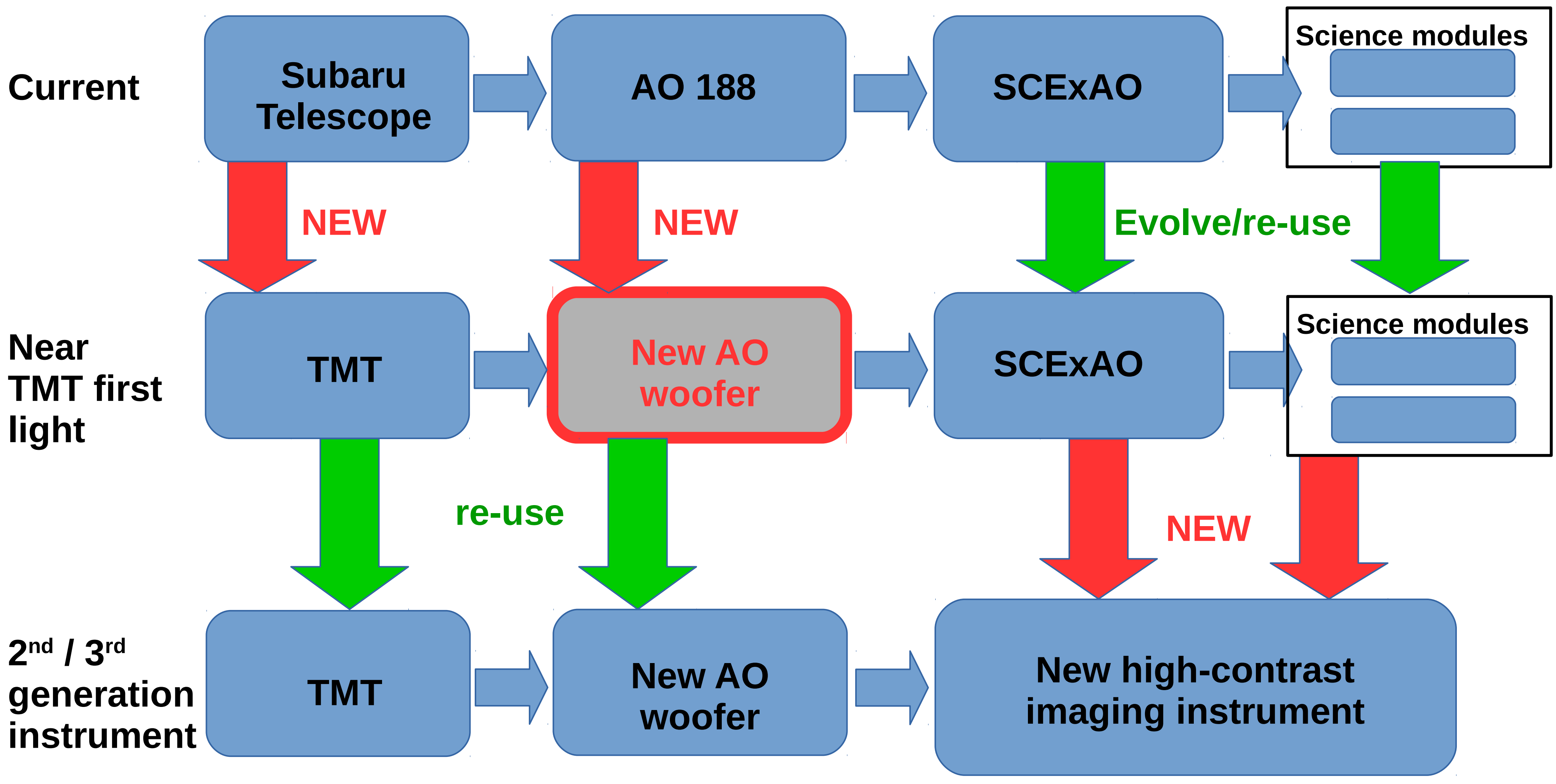
- →**mitigates risks,** minimizes need for engineering time on TMT
- → **benefits from yrs of experience** on Subaru (loop control, data reduction algorithms, observing strategy)

→ Subaru provides path to quickly and safely integrate/validate new technologies prior to instrument deployment on TMT

Open international effort engaging TMT partners.
Expected overlap with development team of 2nd generation, more capable ExAO system. Re-use experience/technologies and possibly hardware to reduce schedule/cost/risk of 2nd generation instrument.

Notional plan toward TMT instrument

Path to TMT requires new AO woofer (~120x120 DM elements) to be built.
Likely US/Japan/Canada joint effort



Conclusions

Habitable planets can be imaged on ELTs (physics and nature are on our side)

ELTs can operate at ~1e-5/1e-6 raw contrast and photon-noise limited detection limit

→ characterization (spectroscopy) of 1e-8 habitable planets accessible around dozens of nearby stars, mainly near-IR/visible

Ideal targets are M0-M5 stars within 5pc

BUT: conventional instrument development process is slow compared to the pace of science in technology progress in our field

→ Schedule for (near-)first light instrument on ELT is very challenging… still lots of work to be done

→ We are exploring, and advocating for a fast path from 8-m telescope to TMT, to yield early science and mitigate risks for longer path $2^{nd}/3^{rd}$ generation instrument